4

NATIONAL NUCLEAR ENERGY SERIES
Manhattan Project Technical Section

Division IV — Plutonium Project Record
Volume 8

OPTICAL INSTRUMENTATION

270

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OPTICAL INSTRUMENTATION

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OPTICAL INSTRUMENTATION

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FOREWORD

Since the discovery of practical means of utilizing the energy of the atomic nucleus, a large and complex atomic energy industry has begun in the United States. As a result of conditions in the world, external to the United States, the requirements of national security have been paramount in our development of this industry thus far. Constant and increasing attention, however, has been given to the problems of economic nuclear power and to the medical and industrial applications of radioactive materials with a view toward "improving the public welfare, increasing the standard of living, strengthening free competition in private enterprise, and promoting world peace." To this end the Atomic Energy Commission has sought the most effective means to accelerate the practical exploitation of nuclear data by American science and industry. The National Nuclear Energy Series is designed to provide for scientists and engineers as comprehensive a source of such data as is possible. The scope of the information presented in these volumes is a measure of American achievements to date in the field of atomic science.

Lewis L. Strauss, Chairman
U. S. Atomic Energy Commission

ACKNOWLEDGMENT

The Manhattan Project Technical Section of the National Nuclear Energy Series embodies results of work done in the nation's wartime atomic energy program by numerous contractors, including Columbia University. The arrangements for publication of the series volumes were effected by Columbia University, under a contract with the United States Atomic Energy Commission. The Commission, for itself and for the other contractors who contributed to this series, wishes to record here its appreciation of this service of Columbia University in support of the national nuclear energy program.

PREFACE

This volume is one of a series which has been prepared as a record of the research work done under the Manhattan Project and the Atomic Energy Commission. The name Manhattan Project was assigned by the Corps of Engineers, War Department, to the far-flung scientific and engineering activities which had as their objective the utilization of atomic energy for military purposes. In the attainment of this objective, there were many developments in scientific and technical fields which are of general interest. The National Nuclear Energy Series (Manhattan Project Technical Section) is a record of these scientific and technical contributions, as well as of the developments in these fields which are being sponsored by the Atomic Energy Commission.

The declassified portion of the National Nuclear Energy Series, when completed, is expected to consist of some 60 volumes. These will be grouped into eight divisions, as follows:

Division I — Electromagnetic Separation Project
Division II — Gaseous Diffusion Project
Division III — Special Separations Project
Division IV — Plutonium Project
Division V — Los Alamos Project
Division VI — University of Rochester Project
Division VII — Materials Procurement Project
Division VIII — Manhattan Project

Soon after the close of the war the Manhattan Project was able to give its attention to the preparation of a complete record of the research work accomplished under Project contracts. Writing programs were authorized at all laboratories, with the object of obtaining complete coverage of Project results. Each major installation was requested to designate one or more representatives to make up a committee, which was first called the Manhattan Project Editorial Advisory Board, and later, after the sponsorship of the Series was assumed by the Atomic Energy Commission, the Project Editorial Advisory Board. This group made plans to coordinate the writing programs at all the installations, and acted as an advisory group in all matters affecting the Project-wide writing program. Its last meeting was held on Feb. 9, 1948, when it recommended the publisher for the Series.

The names of the Board members and of the installations which they represented are as follows:

Atomic Energy Commission	
Public and Technical Information Service	Alberto F. Thompson
Technical Information Division, Oak Ridge Extension	Brewer F. Boardman
Office of New York Operations	Charles Slesser, J. H. Hayner, W. M. Hearon *
Brookhaven National Laboratory	Richard W. Dodson
Carbide & Carbon Chemicals Corporation (K-25)	R. B. Korsmeyer, W. L. Harwell, D. E. Hull, Ezra Staple
Carbide & Carbon Chemicals Corporation (Y-12) †	Russell Baldock
Clinton Laboratories ‡	J. R. Coe
General Electric Company, Hanford	T. W. Hauff
General Electric Company, Knolls Atomic Power Laboratory	John P. Howe
Kellex Corporation	John F. Hogerton, Jerome Simson, M. Benedict
Los Alamos	R. R. Davis, Ralph Carlisle Smith
National Bureau of Standards	C. J. Rodden
Plutonium Project	
Argonne National Laboratory	R. S. Mulliken, H. D. Young
Iowa State College	F. H. Spedding
Medical Group	R. E. Zirkle
SAM Laboratories §	G. M. Murphy
Stone & Webster Engineering Corporation	B. W. Whitehurst
University of California	R. K. Wakerling, A. Guthrie
University of Rochester	D. R. Charles, M. J. Wantman

* Represented Madison Square Area of the Manhattan District.

† The Y-12 plant at Oak Ridge was operated by Tennessee Eastman Corporation until May 4, 1947, at which time operations were taken over by Carbide & Carbon Chemicals Corporation.

‡ Clinton Laboratories was the former name of the Oak Ridge National Laboratory.

§ SAM (Substitute Alloy Materials) was the code name for the laboratories operated by Columbia University in New York under the direction of Dr. H. C. Urey, where much of the experimental work on isotope separation was done. On Feb. 1, 1945, the administration of these laboratories became the responsibility of Carbide & Carbon Chemicals Corporation. Research in progress there was transferred to the K-25 plant at Oak Ridge in June, 1946, and the New York laboratories were then closed.

PREFACE

Many difficulties were encountered in preparing a unified account of Atomic Energy Project work. For example, the Project Editorial Advisory Board was the first committee ever organized with representatives from every major installation of the Atomic Energy Project. Compartmentation for security was so rigorous during the war that it had been considered necessary to allow a certain amount of duplication of effort rather than to permit unrestricted circulation of research information between certain installations. As a result, the writing programs of different installations inevitably overlap markedly in many scientific fields. The Editorial Advisory Board has exerted itself to reduce duplication in so far as possible and to eliminate discrepancies in factual data included in the volumes of the NNES. In particular, unified Project-wide volumes have been prepared on Uranium Chemistry and on the Analysis of Project Materials. Nevertheless, the reader will find many instances of differences in results or conclusions on similar subject matter prepared by different authors. This has not seemed wholly undesirable for several reasons. First of all, such divergencies are not unnatural and stimulate investigation. Second, promptness of publication has seemed more important than the removal of all discrepancies. Finally, many Project scientists completed their contributions some time ago and have become engrossed in other activities so that their time has not been available for a detailed review of their work in relation to similar work done at other installations.

The completion of the various individual volumes of the Series has also been beset with difficulties. Many of the key authors and editors have had important responsibilities in planning the future of atomic energy research. Under these circumstances, the completion of this technical series has been delayed longer than its editors wished. The volumes are being released in their present form in the interest of presenting the material as promptly as possible to those who can make use of it.

The Editorial Advisory Board

The Manhattan Project Technical Section of the National Nuclear Energy Series is intended to be a comprehensive account of the scientific and technical achievements of the United States program for the development of atomic energy. It is not intended to be a detailed documentary record of the making of any inventions that happen to be mentioned in it. Therefore, the dates used in the Series should be regarded as a general temporal frame of reference, rather than as establishing dates of conception of inventions, of their reduction to practice, or of occasions of first use. While a reasonable effort has been made to assign credit fairly in the NNES volumes, this may, in many cases, be given to a group identified by the name of its leader rather than to an individual who was an actual inventor.

PLUTONIUM PROJECT RECORD FOREWORD

This report is a technical account of information collected while developing methods for producing plutonium. Some of the information deals directly with nuclear physics and chemistry. Most of it is related rather to technical processes that needed to be performed in preparation for making the plutonium. These publications represent selections from the great mass of current reports, made on the basis of their value to basic science and technology.

The current technical reports, written during the war years, were essential to the active work of the plutonium project. They supplied needed data and calculations to those who were planning the new processes. Selecting from this mass of records the most reliable data and presenting them in a useful form has been an enormous task, for which the writers and editors of these volumes deserve the sincere thanks of their scientific colleagues. Many fields of science and technology will develop more rapidly because of this knowledge.

The efforts of the men who did this research resulted in the successful production of atomic bombs, which shortened the war and saved the lives of many of their comrades. But in the long view of history it is probable that the major human heritage from their work will not be this quick victory. It may not even be the useful applications of atomic energy, which was first presented as a Promethean gift to man. It is not unlikely that the scientific information in these pages may be the starting point to new reaches of knowledge, which will give to man an understanding that will truly enrich his life.

Arthur H. Compton

INTRODUCTORY NOTE ON THE PLUTONIUM PROJECT RECORD

Organization and Record of the Metallurgical Project. The Plutonium Project Record, which forms Division IV of the National Nuclear Energy Series (NNES), is the scientific and technical record of the former Metallurgical Project. The project had its origin in work carried on in 1940-1941, mainly at Columbia and Princeton on the development of the chain-reacting pile and at the University of California at Berkeley on the production and chemistry of transuranic elements. In January 1942 this work was concentrated in the newly organized Metallurgical Laboratory at Chicago under the leadership of A. H. Compton. The Metallurgical Project grew out of the Metallurgical Laboratory. The initial objectives of the Metallurgical Laboratory were (1) to develop chain-reacting piles to produce plutonium and (2) to develop fission bombs. Major associated units were organized in 1942 at Iowa State College (chemistry and metallurgy) at Ames, Iowa, under F. H. Spedding; at the University of California (chemistry) at Berkeley, Calif., under W. M. Latimer and E. D. Eastman, continuing the previous work there; and at Massachusetts Institute of Technology (metallurgy) under J. Chipman and later M. Cohen. Early in 1943 the work on fission bombs was transferred to an independent project at Los Alamos.

After the successful demonstration of a nuclear chain reaction in the West Stands pile at Chicago in December 1942, the Argonne Laboratory with its experimental pile was built west of Chicago, and the Clinton Laboratories with their pilot-plant pile were built at Oak Ridge, Tenn.—both in 1943. The three major laboratories at Chicago, Argonne, and Clinton, the associated laboratories at Ames, Berkeley, and M.I.T., and some seventy other cooperating groups then constituted the Metallurgical Project, under A. H. Compton as Project Director. Closely cooperating in the transition from laboratory and pilot-plant to large-scale operation was E. I. du Pont de Nemours & Company, which was made responsible for the design and construction of the Clinton pile and for the design, construction, and operation of the Hanford Plutonium Plant. The Project continued as such until June 30, 1945, when it was dissolved.

The Plutonium Project Record (PPR) covers most of the scientific and technical work of the Metallurgical Laboratory and the Metallurgical Project up to the date of the dissolution of the Project, and also

the continuation of this work in the successor laboratories up to approximately Jan. 1, 1946, or in some cases to a later date. In addition, the PPR covers in part the pre-1942 work at Columbia, Princeton, and Berkeley. The record of the work directly leading up to the Los Alamos Project, however, is omitted. Nevertheless the PPR and the Los Alamos Technical Series (Division V of the NNES) cover closely related and in part overlapping subject matter in some of their volumes, particularly in nuclear physics and in chemistry and metallurgy of plutonium.

Important phases of the work of the Metallurgical Project that are not reported in the PPR but will be reported elsewhere in the NNES are as follows: (1) Division VII, the report of the Materials Procurement Project, includes certain early work on process metallurgy, which was initiated largely by the Metallurgical Laboratory. (2) The Division VIII NNES volumes on Analytical Chemistry, which developed from two volumes originally planned as part of the PPR, contain much Metallurgical Project work, including one complete Collected Papers volume. (3) The Division VIII NNES volumes on Uranium Chemistry, which were planned and carried out under the supervision of the PPR editorial group, likewise contain much Metallurgical Project work, including one complete Collected Papers volume.

History and Plan of the Plutonium Project Record. During the war years the scientific and technical work of the Metallurgical Project and its associated laboratories was described currently in a series of reports called the "C reports." The work up to July 1, 1945, was described in some 3,000 reports. After that date the Clinton Laboratories reports became a separate series, but reports of the other units of the former Metallurgical Project continued to be issued as C reports. Most of the C reports were preliminary or semifinal reports. The main consideration during the wartime development was speed of issue and distribution.

As the mass of scientific and technical knowledge obtained on the Project piled up, an increasing need was apparent for its digestion into survey or summary form. In partial answer to this need, an editorial group was set up in the spring of 1943 to organize a Project Handbook. Although never fully completed because of the engrossment of authors in immediately urgent tasks and because of the transfer of many of them to other sites, enough of the Project Handbook was finished to be of real value.

By the summer of 1944, the Metallurgical Project had largely concluded its major task, that of providing the scientific and pilot-plant know-how for the design of the large-scale Hanford Plutonium Plant. The time seemed ripe to plan a series of volumes in which the Project's fund of accumulated scientific and technical knowledge would be

recorded. These would replace the often sketchy and sometimes mutually contradictory C reports and fill many gaps of unwritten knowledge. In the early planning, Laurence L. Quill as Chief of the Editorial Section of the Project Information Division during the summer of 1944, Eugene Rabinowitch, and H. H. Goldsmith made important contributions. After several committee meetings, a plan for the preparation of a Metallurgical Project Record was approved by the Project Director in the fall of 1944. Later, in 1945, the name was changed to Plutonium Project Report or Record (PPR).

When the PPR was organized, rigid compartmentation was still in effect between the Metallurgical Project and the other Manhattan District projects. Members of each project were in general not supposed to know even the major objectives or main outlines of the other projects. The PPR had therefore to be planned as an independent entity. Nevertheless, at its inception the idea was firmly held that later on the Record should become part of a larger series covering the work of all the atomic energy projects. This idea was repeatedly advocated and led in late 1945 to the plan for the Manhattan Project Technical Series (MPTS), a name which was finally revised to the present designation of National Nuclear Energy Series (NNES).

The general plan of organization of the PPR was that of a series of some twenty Survey volumes, called "A volumes," each documented by a like-numbered Collected Papers volume (or volumes); these were called "B volumes." In general, following somewhat a pattern set by the Project Handbook, a Survey volume was planned for each scientific or technical subject to which the Metallurgical Project had made sufficiently major contributions. Each Survey volume was intended to be a fairly complete review or monograph (or else a collection of review chapters) on the subject field. It was planned to cover work done both within and outside the Metallurgical Project, though with primary emphasis on the former, outside work being included only for the sake of accuracy and completeness.

In contrast to the Survey volumes, each Collected Papers volume was designed to consist of individual papers, mostly from individual laboratories and more or less similar to articles in the scientific journals; they were to include only work done within the Project. In planning the PPR, it was realized that some of the Survey volumes would overlap with possible volumes of other projects, but because of compartmentation restrictions, it was decided to proceed in general with the plan as outlined. An exception was the field of uranium chemistry, where it was obvious that all the major projects were making important contributions. In this field, a Handbook of Uranium Chemistry was planned early in 1944, to be edited and written at the Metallurgical Laboratory at Chicago, but as a cooperative effort of all the

projects, and based on a full interchange of information among them. When the Record was organized, this volume was tentatively included as one of the PPR Survey volumes, to be accompanied by a corresponding Collected Papers volume covering Metallurgical Project work only. Later, when the MPTS (now NNES) was organized, these volumes, with the addition of Collected Papers from the other projects, were transferred to the over-all Division (Division VIII) of the technical series. In the field of analytical chemistry, a Survey volume and a Collected Papers volume were planned for the PPR and were well on their way toward completion. When the MPTS was organized, the content of these volumes was pooled with the work of other projects of the Manhattan District to form Survey and Collected Papers volumes of Division VIII of the MPTS. In certain other fields, pooling of material from the different projects was also considered, but was felt to involve too large a task of reorganization.

Because of the wide variety of subject matter, the organization of the PPR into Survey volumes, each accompanied by one or more Collected Papers volumes, is not always consistently followed. There are a few Collected Papers volumes without corresponding Survey volumes, and the converse is also true. Furthermore, the form of organization varies considerably from one volume to another because of varying subject matter and the preferences of the different volume editors and committees.

When the PPR plans were approved toward the end of 1944, the completion deadline for the manuscripts was set for June 30, 1945, the date of dissolution of the Metallurgical Project. Most of the PPR volumes were organized into three groups: (1) chemistry and metallurgy; (2) physics and related engineering; (3) biology and medicine. The first task was to obtain volume editors and editorial committees for the various volumes, to plan the contents, and to find authors. John C. Warner, as chemistry editor of the PPR and Chief of the Editorial Section of the Project Information Division from December 1944 to June 30, 1945, made decisive contributions to the chemistry and metallurgy volumes and to the general planning of the PPR.

The organization of the volumes on physics and on biology and medicine went more slowly, partly because the subject matter was then less ripe for writing than was that on chemistry and metallurgy, partly because of the demands for continuing research and, in the field of instrumentation, for production of instruments to be used at Los Alamos, Hanford, and other sites. Eugene P. Wigner, Frederick Seitz, and H. H. Goldsmith took an active part in the early organization of the physics volumes. Plans for the volumes on biology and medicine were very effectively organized by Raymond E. Zirkle as PPR editor for these fields, with the backing of Robert S. Stone as Associate

Project Director for Health. Hoylande D. Young entered the PPR program as Technical Editor in charge of final editing and processing of manuscripts, and after June 30, 1946, became General Editor.

After the organization of the PPR, steady progress was made in the work of writing and editing, but at a slower pace than was originally hoped. The dissolution of the Project on June 30, 1945, with the readjustments and administrative problems involved in a 50 per cent cut of total personnel; the end of the war after the bomb was dropped in August and the subsequent deep preoccupation and extensive activities of Project personnel in connection with the social and political implications of atomic energy and atomic warfare; new research and planning directed toward the postwar continuation of the atomic energy program; all these slowed the progress of the PPR writing program. During this difficult period, invaluable encouragement and support of the PPR program came from, among others, Norman Hilberry, Associate Director of the Metallurgical Project up to the time of its dissolution, and Farrington Daniels, Director of the Metallurgical Laboratory in 1945-1946.

Meantime, other projects in the Manhattan District group began the preparation of final accounts of their work. In particular, the Los Alamos Technical Series was begun in 1945. Finally, the MPTS (now the NNES) was organized under the Manhattan District Editorial Advisory Board late in 1945. Under the chairmanship of Alberto F. Thompson, as Chief of the Publications Section of the Research Division of the District, this group began the task of coordinating existing writing activities and filling the gaps in these, with the objective of producing a reasonably well-rounded series of volumes covering the work of the entire District. During early 1946, rules for declassification were set up, and the editors of the MPTS volumes faced the difficult task of dividing the subject matter of their volumes into declassifiable parts, publishable immediately, and classified parts, for which publication must be deferred. In June 1947 the completion of the editorial work of the PPR, as part of the NNES, was taken over by the Technical Information Division of the Atomic Energy Commission, at Oak Ridge, Tenn.

In addition to those named above, many other project members worked together in planning the PPR. After the general plans were made, the actual work of preparing the various volumes was in the hands of the volume editors, volume editorial committees, and authors, as described in the prefaces of the individual volumes.

Robert S. Mulliken
Editor-in-Chief,
Plutonium Project Record

VOLUME PREFACE

During the short period between the start of the Optics Section of the Metallurgical Laboratory in the fall of 1943 and its disbandment in the summer of 1945, the Section was called upon to design and build many dozens of optical instruments for remote control in irradiated areas. Practically all of these were to be used under conditions never before encountered, and materials suitable for these conditions either did not exist or were not at all plentiful. At the same time, members of the Section saw clearly that in order to meet the future needs of the new and rapidly expanding technology introduced by the release of nuclear energy it was imperative to study novel principles of design and institute research into the development of optical glasses which would withstand the destructive effects of high-energy radiations. This work and the use of plastic lenses in instruments of high quality and resolution are discussed at length.

The study of principles and reports on design give a comprehensive picture which will be extremely helpful to anyone faced with the necessity of equipping research or industrial laboratories where atomic energy is in use.

In Part I of this volume are presented the fundamental requirements as they appeared at the time and the general way in which they were met. Part II is a series of condensed reports describing typical instruments which were built and certain technical processes, the study of which was essential to the work of the Section.

George S. Monk

January 1954

CONTENTS

Part I

SURVEY OF OPTICAL AND ASSOCIATED PROBLEMS

Chapter 1

OPTICAL PROBLEMS IN THE METALLURGICAL PROJECT

Most of the optical problems peculiar to the Metallurgical Project arise from the need for visual observation of areas that must be shut off from the observer by the heavy shields provided for the protection of personnel against biologically harmful radiation. During the early days of the Project, mirrors and other simple devices were used, but in most cases these were inadequate.

During the summer of 1943 the Optics Section was organized under George S. Monk, and a program of research was instituted. Initially there were two groups: Group 1, Instrument Construction, and Group 2, Metallic Evaporations. These groups were organized to study the problems of mirror materials, low-reflection coating of optical surfaces, and measurements of reflection and transmission. Later Group 3, Optical Design, was added because the unique optical materials and designs needed by the Project required special research.

In the design of optical instruments for Project areas, it was not always easy to foresee the particular sort of instrument that would be most appropriate in any location; however, in most cases the following requirements had to be met:

1. The instrument must be one that essentially moves the eye to the other side of a radiation shield.

2. It must enable the eye to scan the area at the other side of the shield.

3. It must, by reason of its construction, its shape, or the aperture through which it is introduced, shield the observer from radiation.

4. Its optical parts either must be protected from coloration by radiation or must be of materials not so colorable.

Problems arising in connection with the design of optical instruments to meet these requirements may be divided into two groups: (1) those involving principles of optics and (2) those concerned with mechanical construction.

Standard texts[1–6] should be referred to for discussions of general and established principles of optical engineering. The application of some of these principles to Project problems is reviewed in Sec. 1.

1. PROBLEMS IN PRINCIPLES OF OPTICS

1.1 Optical Aberrations. Perfect imagery is never possible, and the ordinary faults of instruments must be taken into account. In general, Project demands for high correction are not excessive. In few cases is it desirable to do more than see what is going on in an irradiated area in familiar and easily recognizable surroundings. High magnification and the best definition are needed only when measurement is required, which is not often.

Some development work was carried out on aspheric systems for use in the over-all viewer (see Sec. 2.4), especially for the purpose of correcting distortion. Except for this and for wide-angle periscopic systems, lens calculations and ray tracing were of a limited character and according to standard procedures.

1.2 Brightness of Images. It is important that the amount of light reaching the eye should be sufficient for the best definition obtainable with a given instrument. In practice it is often considered sufficient to make the instrument and then step up the illumination to a stage that will satisfy the observer. There are, however, several considerations which, if properly employed, may provide guidance in design.

The sizes of entrance and exit pupils are a matter of importance. From a point object all light which succeeds in reaching the exit pupil passes through the entrance pupil of the system. Light losses in the system will cut the intensity down, but should the entrance pupil be sufficiently larger than the exit pupil to more than compensate for these, the intensity of a point will be increased. Actually, small details that are to be picked out of a background may often be considered as point objects.

Another consideration depends on the relation between visual acuity and brightness. According to reliable experimental evidence,[7] the ratio of the least perceptible brightness difference to the brightness at which it is measured ($\Delta B/B$) is fairly constant over a large range. This range is from about 1 to 100,000 candles/sq m and is approximately the range from ordinary interior illumination to the brightest daylight. On the other hand, the visual acuity[8] of the eye (the fovea centralis) varies quite sharply over the lower and middle portions of the same range.

For the normal eye, with no lens defects, visual acuity is generally considered to be dependent on the threshold response of cones in the

retina (and rods for peripheral and twilight vision). Insufficient anatomical data exist for the support of a completely satisfactory explanation of observations. Numerous data by Koenig and others give the relation[9] shown in Fig. 1.1.

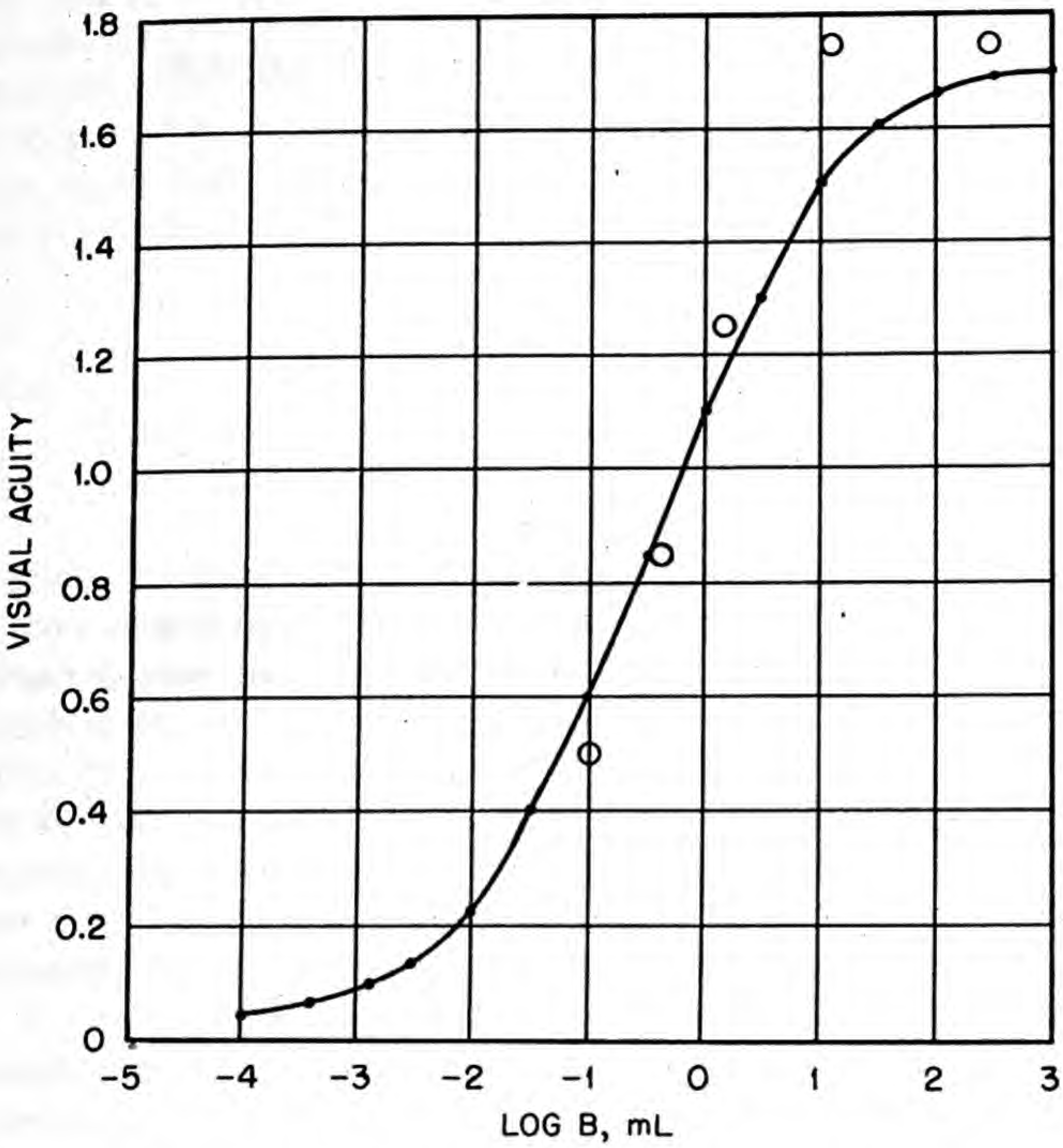

Fig. 1.1—Relation between visual acuity and brightness.

To check the application of these data, measurements of brightness were made through a newly constructed periscope (706-CBX)[10] of unusually good light transmission. The object was a National Bureau of Standards resolution chart. The brightness of the chart was varied over a range from 0.1 to 1230 mL. Measurements of brightness at the chart and through the periscope showed the transmission to be very close to 60 per cent. The resulting values of log B are indicated on the graph by circles. The indicated values of visual acuity are shown in the first column of Table 1.1, and in the second column are the numbers of lines on the chart which could be resolved in each case.

The form of the curve but not the actual slope is confirmed. A correcting factor not considered was the possible dilation of the pupil, which would tend to reduce the slope of the curve connecting the dots.

It is perhaps well to consider that, whereas the pupil of the eye distends rather rapidly, it takes a matter of minutes for photochemical

Table 1.1 —Relation of Visual Acuity and Resolution

Visual acuity	Chart lines (per in.) resolved
0.60	10
0.81	17
1.17	25
1.49	35
1.68	35

dark adaptation of the retina. Considered in regard to Project instrument construction, the situation is different from that of continuous use of a microscope. The Project operator looks only occasionally into a periscope. Moreover, the rapidity observed for pupil distention is that caused by changing from brilliant surroundings, such as in outdoor sunlight, into a darkened room. The Project operator is usually already in a relatively low illumination. Studies indicate illumination varying from 25 to 200 ft-candles in Project areas under observation, and little can be done to provide a relatively high level of illumination, which would be desirable.

A factor of some importance is the Stiles-Crawford effect.[11–13] Stiles and Crawford discovered that light reaching the fovea centralis through the outer zones of the pupil does not produce the same stimulation as light through the center of the pupil. The effect is in cone vision (daylight vision) only. Actually, the advantage of a large exit pupil in freedom of head position is a more important factor.

1.3 Magnification. The magnification of a telescopic or periscopic instrument varies with distance of the object. In stating the magnification of a given instrument it is important to specify the conditions of use, that is, whether it is for near or far objects, because omission of such specification implies that magnification for objects at a distance is meant.

The degree of magnification will depend in part on what sort of instrument is used. It is not possible to have both high magnification and large angle of view. The over-all viewer, permitting as wide an angle of view as is possible, of necessity imposes a fractional magni-

fication. Lens-containing instruments, whether periscopes or telescopes, are usually instruments of unit magnification or higher. In periscopes the magnification seldom is above 10, although in extreme cases submarine periscopes have magnifications of 30 for nearby objects.

It is important to remember that increased magnification does not always mean higher resolution. Especially in borescopes and other instruments with small aperture and many lens elements, the limit of resolution is set by residual aberrations, imperfections in lens manufacture, imperfections in lens adjustments, and departures from tolerable focal ranges (see Sec. 1.5).

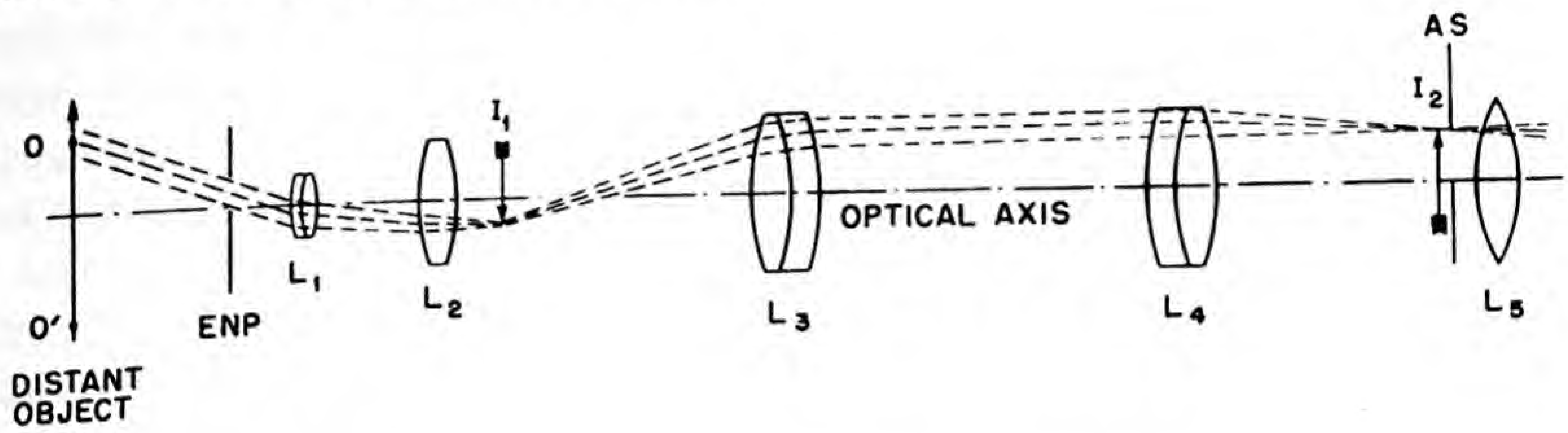

Fig. 1.2—Train of lenses constituting the first part of a periscopic system. L_1, objective; L_2, field lens; L_3, 1st erector; L_4, 2d erector; L_5, field lens; I_1 and I_2, image positions; and ENP, entrance pupil.

1.4 Field of View. In discussing this topic without going at considerable length into the principles of geometrical optics, it is difficult to avoid the appearance of dogmatism. The definition of terms, and hence the discussion of their meaning, becomes obligatory.

In Fig. 1.2 is shown a train of lenses constituting the first part of a periscopic system. It is proposed to show the extent to which the character of these lenses, their diameter, and their spacing determine the field.

The first of these, L_1, is the objective of the system through which all rays incident on the system pass. The function of L_2, a so-called "field lens," is to redirect the focused rays so that they will stay within the confines of a tubular space of which the base is L_3. The field lens L_2 has its function so limited because it is close to the image position I_1. Of course, in addition, L_2 may be so shaped as to aid in the correction of aberration. Lens L_3 has a principal focus at I_1; hence beyond L_3 the rays from any point O will be parallel. In fact, the three lenses would constitute a telescope or a microscope, depending on the relation of their focal lengths.

Other lenses might be added in the train, but for the discussion of the present topic they need not be completely specified.

All that need be specified is that in the whole system there is an aperture which limits the light from every object point. It is important to realize that this aperture has its functions so limited and that it does not limit the field. In a camera it is the iris diaphragm; in a periscope it is usually one of the train of lenses.

By the laws of optics the lenses L_1 and L_2 will together form an image of the aperture stop. In Fig. 1.2 this is ENP, the entrance pupil of the system. Obviously, then, no matter what rays of light from any point in the object field may impinge on L_1, only those which pass through ENP can pass through AS to take part in the formation of the final image. Stray light, a detriment to the image, is of course not considered. By "field of view" then is meant the object field enclosed in the cone having its apex at ENP. Sometimes the "angle of view" is used to describe the size of the field.

It will be seen that the rays from a distant object point, such as O, constitute a bundle which in Fig. 1.2 is represented by three dashed parallel lines. The middle ray is the "chief ray." If O and O′ are at the edges of the observed field, then the angle between them with its apex at ENP is the measure of the field of view. Obviously, one factor in its limitation is the size of L_2. Other limitations may be the sizes of other field lenses in the train, as well as any diaphragm, which are sufficiently close to any image position to cut off the periphery of the image.

Given an objective, a field lens, and other lenses in train capable of delivering to the final image position a stated angle of view, it is a problem to transmit this angle to the eye and at the same time have high magnification. The higher the magnifying power of the eyepiece, the more difficult it is to make it of large diameter. In consequence the diaphragm in front of the field lens of the eyepiece becomes the field stop.

It is also obvious that, in order for field OO′ to be imaged within the confines of lens L_2, lens L_1 must have the required power or degree of convergence of the rays. Primarily then, for a given optical train, the field of view depends on the power of convergence of the objective. However, other field stops or stops of any sort, whether they are exactly at an image position or near enough to affect field size, may render useless the power of the objective. An illustration is a borescope with a total length of 40 ft and an outside diameter of 1⅜ in. The objective was designed for an angle of view above 28 deg. Because of the need for good electrical contacts at the couplings of tube units, the aperture at the positions of these couplings was limited

to ⅝ in. in diameter. In determining the location of these couplings a compromise had to be made. If they were placed too close to the collimating lenses, they would restrict the brightness severely. If placed far away from those lenses, they would limit the field. They were finally put at positions where the total bundle of rays was smallest, that is, in the vicinity of images of the pupils. The compromise resulted in cutting the field by about 20 per cent.

1.5 Definition and Resolution. The actual ability of an optical instrument to resolve two close objects depends not only on the perfection of design and construction but also on the laws of physical optics. Since the image of a point object is not a point but a diffraction pattern of finite size, it becomes necessary to specify the conditions under which two such images of a close pair of points can be distinguished from each other. Obviously, this depends on the quality of the image and the eye of the observer. There also must be considered the ability of the observer, possibly based on familiarity with optical observations or mental adaptability, to draw reasonable inferences from borderline cases. The formula of Rayleigh is generally accepted. If d is the diameter in the image plane of the first dark ring of the diffraction pattern, λ the wavelength, and u′ the half angle of the cone of rays contributing to the image point, by Rayleigh's criterion,

$$d = \frac{1.22\lambda}{\sin u'} \tag{1}$$

It is considered that in actual practice the eye can do better than the limit set by Eq. 1, and it may be accepted as true that with sufficiently good optical design two point images may be separated if their distance D (d/2) apart is given by

$$D = \frac{0.5\lambda}{\sin u'} \tag{2}$$

2. MECHANICAL CONSTRUCTION PROBLEMS

2.1 Coloration of Optical Parts. (a) Selection of Noncolorable Transmitting Media: Use of Plastics and Mirror Systems. Most of the work, both experimental and theoretical, on irradiation coloring has been done on crystals.[14–16] Radiations from radioactive substances color glass by producing absorption bands lying in the visible spectrum region. The character and location of these bands depend on the composition of the glass.

On the Project, glass elements of optical instruments are subjected to gamma and neutron radiation and become darkened sufficiently to be either useless or inefficient. The intensity of radiation to which Project instruments may be subjected varies from the most intense, as in the discharge area of a pile, to very low intensity, as in some hot-cell operations.

Exact data concerning the degree of coloration to be expected are lacking. This is partly because different kinds of glass and other optical materials differ greatly in their resistance to radiation. Such experiments as have been partly completed[17] show that glasses containing no boron are most resistant. Unfortunately, borosilicate crown glass, light barium crown glass, and others containing boron are used very extensively in the design of high-quality optical equipment. The new rare-earth glasses are similarly objectionable. Only two or three little-used optical glasses are highly resistant to coloration, and these glasses do not give the designer much leeway.

Attempts were made to find substitutes for glass. In all cases in which high-energy radiation reaches the scanning element directly, it is advisable to use mirrors rather than glass prisms. Mirrors offered only partial solutions. Designs of periscope and borescope systems containing only mirrors were studied. Some of these are novel, but the light-gathering and transmitting qualities simply do not approach those of refracting media. The best that can be said is that quite often it was found possible to substitute mirrors for prisms wherever the beam had to be turned through an angle. This stimulated research for the best mirror surface. It was found that evaporated chrome-aluminum mirrors on glass had the highest reflection power and at the same time were durable. The most rugged mirrors were of Stellite No. 22. On the other hand these mirrors did not retain their shape if too thin, and the use of thick Stellite plates proved very expensive. Some experiments with Stoodite, a very hard machine-tool alloy, indicated that it might even surpass Stellite in both ruggedness and reflecting power. Unfortunately the work of the section was terminated before these experiments were completed.

The superiority of refracting over reflecting media led to investigation of plastics.[17–19] Some attempts have been made to use plastic prisms, which are much more resistant to coloration. It is much easier to polymerize the plastics in molds than to grind and polish the surfaces, especially in the case of prisms. The difficulties encountered have been forbidding. Although in general the smaller the prism the less danger of optical anisotropy, there is a lower limit to size because of mechanical difficulties in manufacture. Prisms above

a certain size almost always are of poor quality optically. In this field there is much research to be done.

It was found that styrene and cyclohexyl methacrylates were being used extensively in the manufacture of plastic achromats for the armed forces because they possessed the best-known combination of optical and mechanical characteristics. Samples of these two plastics and Lucite were subjected to neutron and gamma radiation. Although the plastics colored, they withstood radiation between 100 and 1000 times as well as the optical glass in common use. This was sufficient to justify their adoption. Styrene and cyclohexyl methacrylate were used principally in making borescope No. 2 and certain other instruments used in pile discharge areas. The Lucite is chiefly used in windows. Up to June 1945, lenses made from these plastics did not darken sufficiently to affect their usefulness.

(b) Baffling to Prevent Coloration. High-energy radiation is not reflected or refracted in the same manner as light by ordinary optical means. In consequence, if space permits, light rays from an object may be reflected into an optical instrument by mirrors that only partially scatter high-energy radiation. This is one type of baffling. On the other hand, the light rays themselves may be made to travel a straight path through the instrument, and the optical parts may be surrounded by materials which are most effective in absorbing the high-energy radiation. This is another type of baffling. Both are used in Project instruments.

In general, a periscope through the shield of a neutron reactor is subject only to gamma and neutron radiation. A satisfactory baffle would consist of three layers. The outer layer would be made of paraffin or some other material containing hydrogen atoms; it would slow most of the neutrons and would make them more easily absorbed by the middle layer. The middle layer would consist of cadmium or boron, the latter probably in the form of boron carbide. The third and inner layer would be lead.

The mean free path of a thermal neutron in powdered boron carbide is about 0.3 mm and in cadmium is about one-tenth as much. Thus the middle layer could be quite thin. When boron absorbs neutrons, high-energy alpha particles are emitted; and when cadmium absorbs neutrons, gamma rays are emitted. The lead in the third layer would afford shielding from these as well as gamma rays directly from the original source of radiation.

By leaving off the outer layer of paraffin, not much additional coloring would result because the fast neutrons are not absorbed by the nuclei in the optical elements. However, more Schott effects are

caused by the Wigner effect of the fast neutrons, and these will provide positions for more electrons to cause F centers.[14]

2.2 Illumination. The problem of field brightness has been treated in Sec. 1.2. The type of lighting best for particular situations will be discussed here.

When a general view is required, as of an interior, floodlighting is effective. On the other hand, in many cases close inspection of details is required, as in certain hot-cell operations where the level of a liquid in a gauge or glass tubing is to be read, with the objective of the periscope close to the object. The best example of this is the use of the borescope to examine the walls of a small-diameter tube for crevices due to corrosion, etching, and mechanical breaks. In this case, illumination by a concentrated point source is preferable to diffuse illumination. The problem is similar to the use of oblique illumination in microscopy. The irregular surface to be examined is full of ridges and peaks which, if seen in sharp outline, are more readily interpretable than if they appear diffuse. Each irregularity is small enough to give a diffraction pattern of the source. If this is a point source, the image is sharper.

2.3 Scanning Problem. The scanning unit, mounted preferably at the entrance pupil of the instrument, may be a prism, a mirror, or a combination of mirrors and/or prisms. The following effects are to be noted.

(a) Reversion of Image. If a single prism is used, it will revert the image. A second prism can be used to restore it, provided it is oriented properly. On the other hand, the second prism can be oriented so as to give a second reversion in a plane perpendicular to the first, the two reversions thus combining to invert the image completely. This is the function of the Porro prism commonly used in binocular telescopes to erect the image.

If two prisms are used, with the first one rotating to perform the scanning operation, it makes a difference which axis of rotation is chosen. If the axis is parallel to the refracting edge, as in Fig. 1.3, the scanning system alone will at all times give an erect image. If the axis is as in Fig. 1.4, the image will turn completely over as the prism is turned through 180 deg. This disadvantage is offset by the fact that this latter system permits scanning through a range of 180 deg without rotation of the entire periscope, whereas the former can scan only 90 deg with a single orientation of the periscope. The turning over of the image can be compensated for by a Dove prism elsewhere in the system.

Reversions and inversions due to mirrors are the same as those due to prisms when used as described. Combinations of mirrors and prisms may be employed.

(b) Aberrations. Because of the spherical aberration due to refraction of a convergent or divergent bundle of rays at a plane surface, prisms for scanning purposes are free from this aberration only when the objects are at some distance; thus rays from a point are sensibly parallel. This is nearly always true with periscopic instruments. In

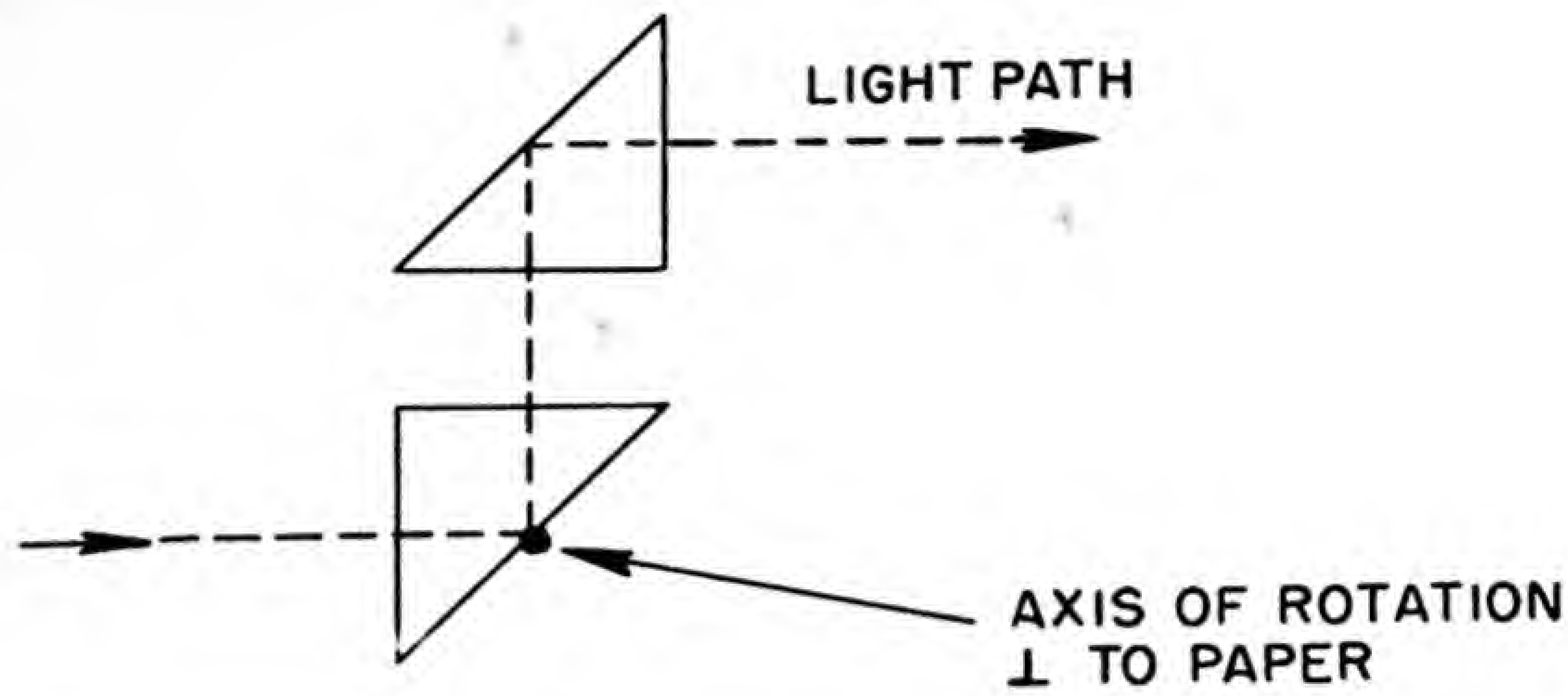

Fig. 1.3—Scanning unit with two prisms; the axis of rotation is parallel to the refracting edge.

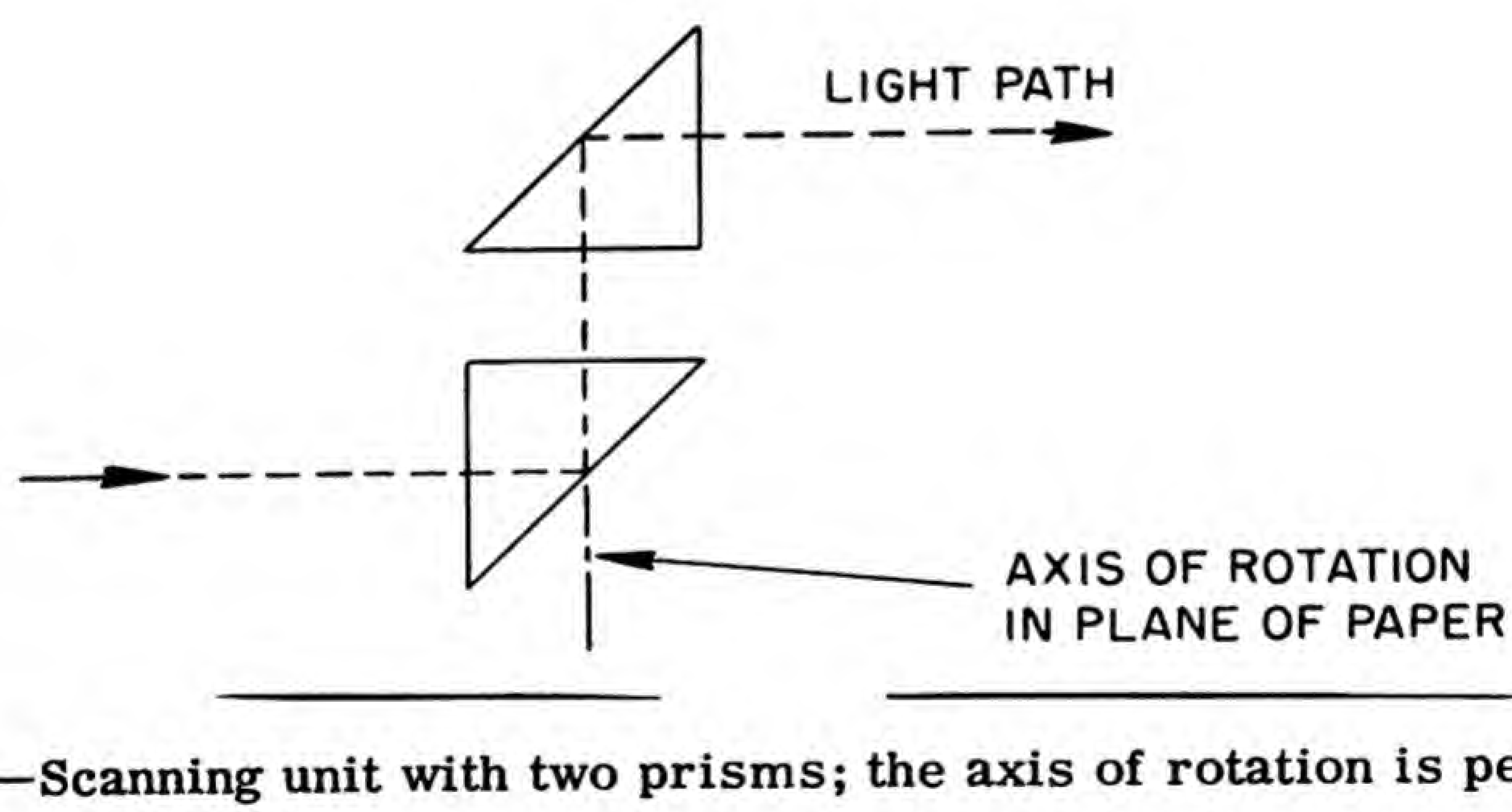

Fig. 1.4—Scanning unit with two prisms; the axis of rotation is perpendicular to the refracting edge.

the borescope, although the object is close, usually the smallness of the entrance pupil restricts the size of the ray bundle, and consequently spherical aberration is not severe. In any case, where all elements of a system are designed to work together, corrections for spherical aberration can be made. In addition to spherical aberration, there is a small amount of chromatism due to a prism. Both aberrations can be avoided by the use of mirrors.

(c) Limitation on Angle of View. An outstanding problem is the requirement for a large angle of view, but this is still largely unsolved.

The critical angle γ_c of refraction of a refracting medium of index n is given by $\sin \gamma_c = 1/n$. This imposes a limit on the angle of view obtainable with a 45-deg scanning prism. From Fig. 1.5 it can be shown that, in viewing objects at 90 deg, the angle of view on one side is limited by $i = \arcsin [n(45 - \gamma_c)]$. For a glass index of 1.52 (borosilicate crown), the value of γ_c is about 41 deg and i is about 6°5′. For higher indices the angle i is larger. On the other hand, borosili-

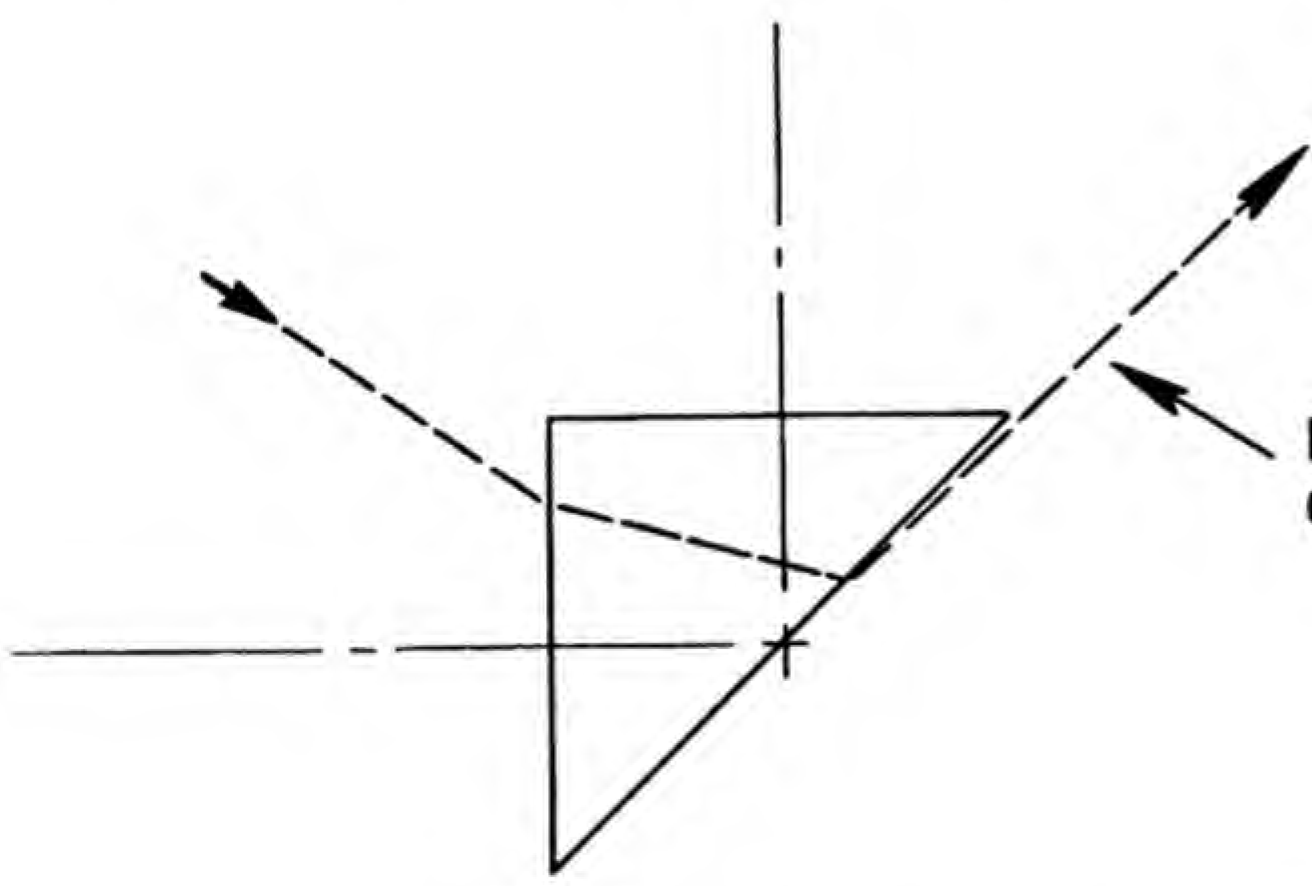

Fig. 1.5—A 45-deg scanning prism showing the limitation on the angle of view when viewing objects at 90 deg.

cate crown glass is optically superior for prisms because of its freedom from bubbles and striae. The limitation can be avoided by coating the diagonal face with aluminum or platinum, but this results in a lowering of light efficiency.

The difficulty can be avoided also by using a mirror. Here, too, the light efficiency is less than for a prism. Since mirror surfaces are subject to tarnishing, metallically coated prisms are usually used.

Certain plastic lenses made for use in military vehicles had extremely large aperture ratios. One system had an exit pupil 5 in. from the rear face of the eyepiece and about ⅝ in. in diameter. Adoption of plastic lenses introduces a problem of new design. At present only two plastics are available for such lenses, and the optical designer, with this insufficient variety in optical constants, must produce systems as free from aberrations as with glass. In so far as plastic lenses already designed were available, these were used. Much new developmental work in this field is still to be done.

Project conditions called for the development of periscopes with unusually large angles of view and at the same time as much magnification as possible, since in a given instrument one of these is enhanced at the expense of the other. Periscopes were developed in the

laboratory with angles of view as large as 60 deg and better than unit magnification. Since, in view of time and directive restrictions, these periscopes could be made only with available lenses, the best definition was not always obtained. Usually the center of the field was good. A great deal of useful research on this problem is in abeyance at the time of writing.

2.4 Ease of Use by Personnel. In building optical instruments two types of Project personnel had to be considered. Scientific personnel were impatient of mechanical detail. Engineering personnel required that images be properly oriented, that instruments be so mechanically perfected that operations could be routine, and that the operator be positioned as though he were viewing the area with the naked eye. Generally these differences have been met by making each instrument as optically and mechanically perfect as possible because, once they had an instrument, the scientists liked the advantages they had previously belittled.

The factors contributing to ease of use may be classified as "optical" and "mechanical." The primary optical advantages are absence of aberrations, sufficient brightness, good definition, adequate and suitable magnification, absence of inversions or reversions, appropriate depth of focus, correct demarcation of field, and correct positioning of the observer. Most of these have already been discussed in Sec. 1.

Depth of focus must be appropriate for the intended use of the instrument. If an over-all view is required, focusing for different object planes should be reduced to a minimum. This can be easily included in design of a periscope. On the other hand, if (in an extreme case) it is desired to measure by focal change the depth of corrosion, a maximum focusing range is desired. In this case a microscope or telescope will be better.

Demarcation of the field is important psychologically. Often it is necessary to cut into the light beam with a mechanical part, such as a gear or the edge of a scanning mirror. In the final image field this may be sharp or blurred. In either case it serves to distract the observer. Perhaps a blurred edge to the field or an edge with gradually changing brightness is the most troublesome, since the observer will try to discern what lies in the dim boundary region. A circular diaphragm at the final image plane excludes such defects.

Freedom from bodily strain is important in positioning of the observer. The head should be in a comfortable position relative to the standing or sitting position of the body to prevent eyestrain. Positioning may, however, be carried too far. In one instrument, which scanned a large area both vertically and horizontally, the eyepiece

actually turned through 90 deg from a vertical to a horizontal position, and in order for the observer to look horizontally he had to assume a very distorted posture. This was done to allow relatively unskilled and mentally unadaptable personnel to face in the same direction as the instrument. A better solution might have been a partial turn of the eyepiece to indicate the sense of the scanning, but not enough turn to impose a strained posture on the body. In this detail, the character of the personnel destined to use the instrument has to be considered.

In general, for the sake of simplicity and directness of operation, manual control is used unless the unwieldy or massive nature of the instrument makes this difficult. Manual control is also forsaken when the mechanical means necessary to give the operator remote manual control of the instrument are too complicated to be justified on the grounds of the more intimate relation existing between operator and instrument when using manual control.

In certain applications the number of corners around which mechanical remote control would be forced to operate dictates the use of motor control at the objective end of the instruments. The motor control is operated through switches conveniently placed near the eyepiece position. Other instruments have necessarily very constricted portions through which mechanical control devices cannot be tolerated because of the serious limitations they would impose on the optical systems. Under such conditions electric motors with power supplied by small insulated wires are the only reasonable solution. In some instruments the operating space is too small to permit small electric motors of the usual type to be employed; and, if the other restrictions preclude the possibility of mechanical remote control, electrically operated solenoids of very small dimensions, controllable by the observer through rheostats or Variacs, offer a practical solution.

Simple motor control is not deemed satisfactory for the focusing adjustment of optical instruments; consequently all Project instruments have been designed using the fingertip manual control provided by a rack and pinion, simple draw tube, threaded draw tube, or a similar device. Scanning or rotating mirrors and prisms can be satisfactorily operated by motor control, and this method of control has been employed in several of the larger optical instruments. However, most operators express a preference for manual control except where it is obviously not practical.

2.5 Construction Materials. The question of suitable optical materials has been discussed in Sec. 1. The present section is chiefly concerned with materials for the housing, shielding, and manipulating parts of optical instruments developed for Project applications.

Radioactivity is induced in all parts of an instrument bombarded by neutrons. It becomes important to use, wherever possible, materials made of substances having small capture cross sections. Aside from the hazard to personnel, those parts affected are likely further to discolor the glass or other optical elements of the instrument. Long-period-induced radioactivity of dense metals, under certain Project conditions, is a cause for objecting to their use in optical instruments where such an effect may occur. Materials with shorter periods would be more desirable. Of course, hardened-steel gear racks, shafts, and roller and ball bearings are employed as they seem necessary or desirable. The necessity for shielding the operators and in some cases the optical components of instruments from certain radiations requires that thick lead shields be incorporated in the structure of some optical instruments; in such cases this bears a marked influence on the method of control or manipulation of the instruments, as suggested in Sec. 2.4. Other shielding materials, such as cadmium, paraffin, and water, may be desirable in certain installations, and they also impose restrictions on the control means which is to be employed.

In constructing Project optical instruments, lightweight metal parts are desirable to make reasonably large instruments convenient for manual operation. Aluminum and aluminum alloys are used when they are available and when it is possible to take the extra time needed, even with special equipment and techniques, to weld, braze, or solder aluminum and aluminum alloys. Aluminum-alloy castings combined with similar alloy tubing, rod, and plate stock permit the construction of very satisfactory instruments.

When the size of the optical instrument desired is such that it is unwieldy, heavier construction is usually specified; then the matter of weight is no longer given so much importance, and brass and steel are used very largely in the construction of the instruments. Stainless steel is required in the housing or exposed parts of certain optical instruments because of the corroding conditions under which they must be used. Because of its machining characteristics and rather great density, the use of stainless steel has some disadvantages. As mentioned previously, hardened-steel gear racks, shafts, and roller and ball bearings are used when necessary or desirable.

It has been a practice for years to construct most optical instruments used by physicists from brass because of its ease of machining, soldering, and brazing. Brass likewise is used very largely in Project instruments. The chief disadvantages of brass are (1) its large density as compared to aluminum alloys and (2) the ease with which it corrodes, especially in the presence of chemical fumes.

In many cases a glass prism can be protected by a window. Where this is not possible or where frequent removal for cleaning is necessary, metal mirrors are to be preferred. Optical Stellite (reflecting power, 80 per cent) is an extremely hard and corrosion-resistant material and has been used in many Project instruments.

In commercial construction of optical instruments several methods of producing black surfaces on the inside of the instruments are generally employed to baffle stray light or to reduce the reflection of light from interior surfaces or walls of the instruments. In Project instruments wide use is made of thin-walled lightweight black fiber (Bakelite, etc.) tubes as liners between the optical components of the instruments.

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Chapter 2

OPTICAL INSTRUMENTS FOR VIEWING IN IRRADIATED AREAS

In nearly every case where an optical instrument is needed in the Project, it is because of the interposition of a biological shield between the equipment and the operator. The operator must somehow see through the wall. Several types of instruments are useful for this purpose. The application of these various instrument types to Project needs is described in this chapter.

1. WINDOWS

In a restricted sense, which will be adopted here, a window is defined as "an opening through a biological shield, filled with any transparent medium, and having no power of magnification or image-forming characteristics." Perhaps the best examples of such windows are in so-called "hot cells." There is a concrete wall (2 ft thick) surrounding the hot cells, into which were inserted stainless-steel horizontal cylinders about 6 in. in diameter with gasketed plane windows at each end. The cylinders can be filled with distilled water or with water containing in solution some salt or other material which will be more absorbent of radiation.

Important are (1) corrosion of container materials, (2) transparency, (3) turbidity, and (4) effectiveness in stopping radiation.[1] Tests[2] indicate that the least corrosive of satisfactory transparent liquids is $ZnCl_2$. A solution of this salt did practically no damage to metals and gasket material, and it remained transparent for many months.

Other optical hazards are the possibility of bubbles forming on the inside surfaces of the glass windows and of convection currents. If distilled water is used, bubble formation is not a problem, and the convection currents have not been noticed.

The principal limitation on a window is the angle of view. By moving the eye from one side of the exit end to the other, the maximum angle of view obtained is 2d/L, where d is the diameter of the window and L is the length of the tank. Thus with a tank 3 ft long and 6 in. in

diameter, the angle of view is about 18 deg and is limited to the area immediately in front of the tank. This limitation can be overcome in part by the use of movable mirrors, but these must be large and of good quality. Even then, inversions and undesirable orientations of the image will occur unless two mirrors are used.

A drawback not ordinarily considered is the effect of irradiation from outside illumination. When looking into a window of the type described, the observer's attention is distracted by surroundings outside the cell. If these surroundings are bright, perception is lessened.

A window should be prescribed as an auxiliary device or, for that matter, in any situation where an optical device is needed for only a short time and no periscope is available. Even then, standardization[3] of optical equipment, by which an instrument of the most general sort can be made readily available, is to be preferred.

2. LIQUID-FILLED TANK VIEWERS

2.1 General Cases. Liquid-filled tank viewers are known as overall viewers and may be considered as windows looking into the desired areas. Different forms of such a viewer will have different optical properties, depending upon the shape of the light-receiving surface and the liquid, but the general effect of a window will remain. Thus, certain aspects of all types of tank viewers can be discussed generally as follows:

1. The only positions of the eye that will be considered are close to the last surface of the tank; consequently this last surface will have little effect on the quality of the image and will not be discussed.

2. The pupil of the eye in all cases acts as the aperture stop of the system. The cases to be discussed all have the eye located near the bottom edge of the last surface. This position of the eye will afford the largest angle of view. Placing the eye at different positions on the last surface will change the field of view and, in some instances, the angle of view. Unless the dimensions and indices of refraction are known, little can be said about the variation of the angle of view with eye position. It suffices, therefore, to discuss all tanks in terms of the "maximum angle of view."

3. The liquid used in the tank will be chosen not only for its optical properties but also for its radiation-absorbing properties.[2] The amount of absorption required to make the use of such a viewer possible will determine also the length and diameter of the tank.

In the following discussions, certain conventions as to symbols will be observed. Media and quantities corresponding to media will be denoted by odd-number subscripts; surfaces and quantities related to them will be denoted by even-number subscripts. Heights are meas-

ured from the optical axis. The numbering proceeds from left to right, starting with the symbol 0 and the number 1 for the object space. If the center of curvature of a surface is located to the left of the vertex of that surface, its radius will be considered negative; if it is to the right, its radius is positive. Thus in Fig. 2.1 the object of

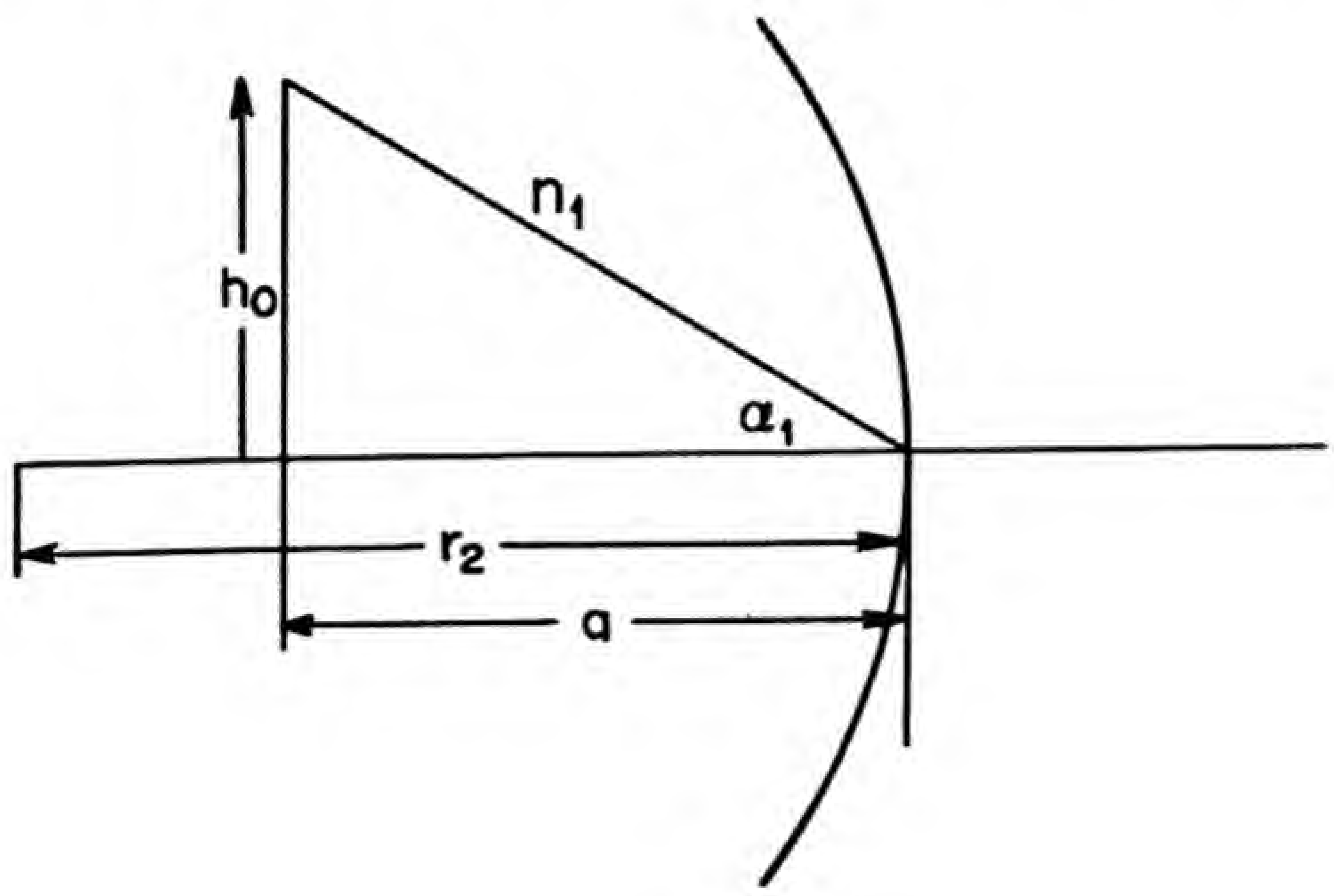


Fig. 2.1—Schematic diagram of an object with a height h_0 and in a medium with an index of refraction of n_1.

height h_0 is in a medium of index of refraction n_1. The ray from the object strikes the surface of radius r_2 at an angle α_1, where

$$\alpha_1 = -\tan^{-1} \frac{h_0}{a}$$

Acute angles will be considered positive if the rotation necessary to bring the ray into coincidence with the axis is clockwise and will be considered negative if the rotation is counterclockwise. In all other cases, regular Cartesian coordinate system conventions apply.

2.2 Case 1: Plane Window. The simplest form of a liquid-filled viewing tank is one with the liquid enclosed between two plane and parallel glass plates which form the first and second refracting surfaces. The thickness of the glass plates may be ignored, and the tank may be considered as a length of optically refractive material of index n_3 surrounded by material of index n_1. The system may be treated schematically as in Fig. 2.2. Let L be the length of the tank and w its width. A ray passing through the tank at angle α_3, where

$$\tan \alpha_3 = \frac{w}{L} \tag{1}$$

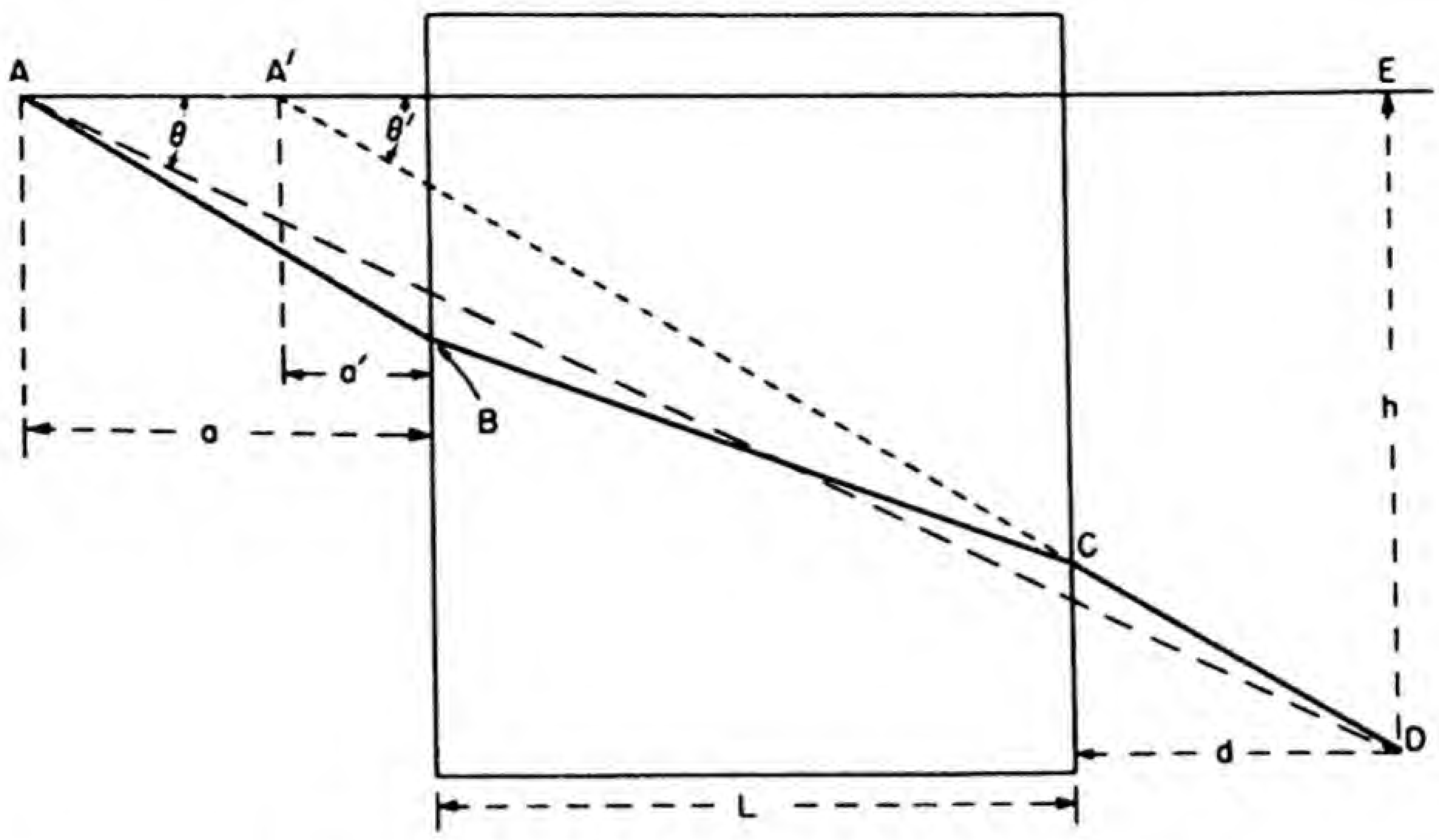


Fig. 2.2—Schematic diagram in which A′ is the apparent position of A through the tank of length L.

makes the largest possible angle through the tank. From Snell's law it follows that

$$n_1 \sin \alpha_1 = n_3 \sin \alpha_3 \tag{2}$$

so that the largest possible angle outside the tank is given by

$$\sin \alpha_1 = \frac{n_3 w}{n_1 \sqrt{w^2 + L^2}} \tag{3}$$

In most cases the object lies in air, for which Eq. 3 is reduced to

$$\sin \alpha_1 = \frac{nw}{\sqrt{w^2 + L^2}} \tag{4}$$

where n is substituted for n_3. Equation 3 may also be rewritten as

$$\alpha_1 = \sin^{-1} \left(\frac{n_3}{n_1 \sqrt{1 + L^2/w^2}} \right) \tag{5}$$

and it is easily seen that α_1 will increase with increasing values of n_3/n_1 and decreasing values of L/w.

The magnification of the system is also important. Consider an object a distance a away from the tank, viewed from a position D on the other side of the tank. If the tank were absent, the path of a ray from a point A would be a straight line AD. When the tank is interposed, the light will be twice refracted, and, in a tank full of a medium

denser than outside, the path of the ray will be ABCD. It can easily be shown from the geometry of the figure that the apparent shift (a − a′) of the object toward the observer is given by

$$a - a' = L\left(1 - \frac{\cos\alpha_1}{n\cos\alpha_3}\right) \tag{6}$$

where α_1 is the angle of incidence of the ray and α_3 is the angle of refraction inside the tank. The index of refraction n is for a denser medium in air and is substituted for n_3/n_1.

The magnification due to the presence of the tank is defined by M = tan θ'/tan θ, where θ' is the angle between AE and AB and θ is the angle between AE and AD. From the figure,

$$\tan\theta' = \frac{h}{a' + L + d} \tag{7}$$

$$\tan\theta = \frac{h}{a + L + d} \tag{8}$$

so that

$$M = \frac{a + L + d}{a' + L + d} \tag{9}$$

By algebraic manipulation and using the relation

$$\sin\alpha_3 = \frac{w}{w^2 + L^2} \tag{10}$$

and Snell's law, Eq. 9 can be written

$$M = \frac{n(a + L + d)}{n(a + d) + L^2 + w^2(1 - n^2)} \tag{11}$$

It follows from Eq. 11 that, if a or d is sufficiently large in respect to L, the magnification will be negligible. Also, the greater the index of refraction of the material in the tank, the greater will be the magnification for a given angle of view and the shorter will be the apparent length L of the tank.

The field of view through such a tank is curved. Consideration of the foregoing analysis shows this to be true, and the exact shape of the curve can be calculated. It is sufficient to point out, however, that,

since the difference between α_3 and α_1 depends on Snell's law, it is not linear but increases more rapidly as larger angles α_1 are considered. Thus, to an observer standing in front of the tank and looking at a row of objects lined up parallel to the end of the tank, they will appear to lie on a curve bowed away from him at the middle. The greater L is, the greater will be the bow, and the larger d or a is, the less the field will appear curved.

2.3 Case 2: Curved Window of Negligible Thickness. The simplest possible change in a tank viewer to increase angular field is the use of a curved window on the front surface. As before, the thickness of the windows may be ignored, and the tank may be considered to be an extremely thick concave-plane negative lens with an index of refraction equal to the index of the liquid (see Fig. 2.3).

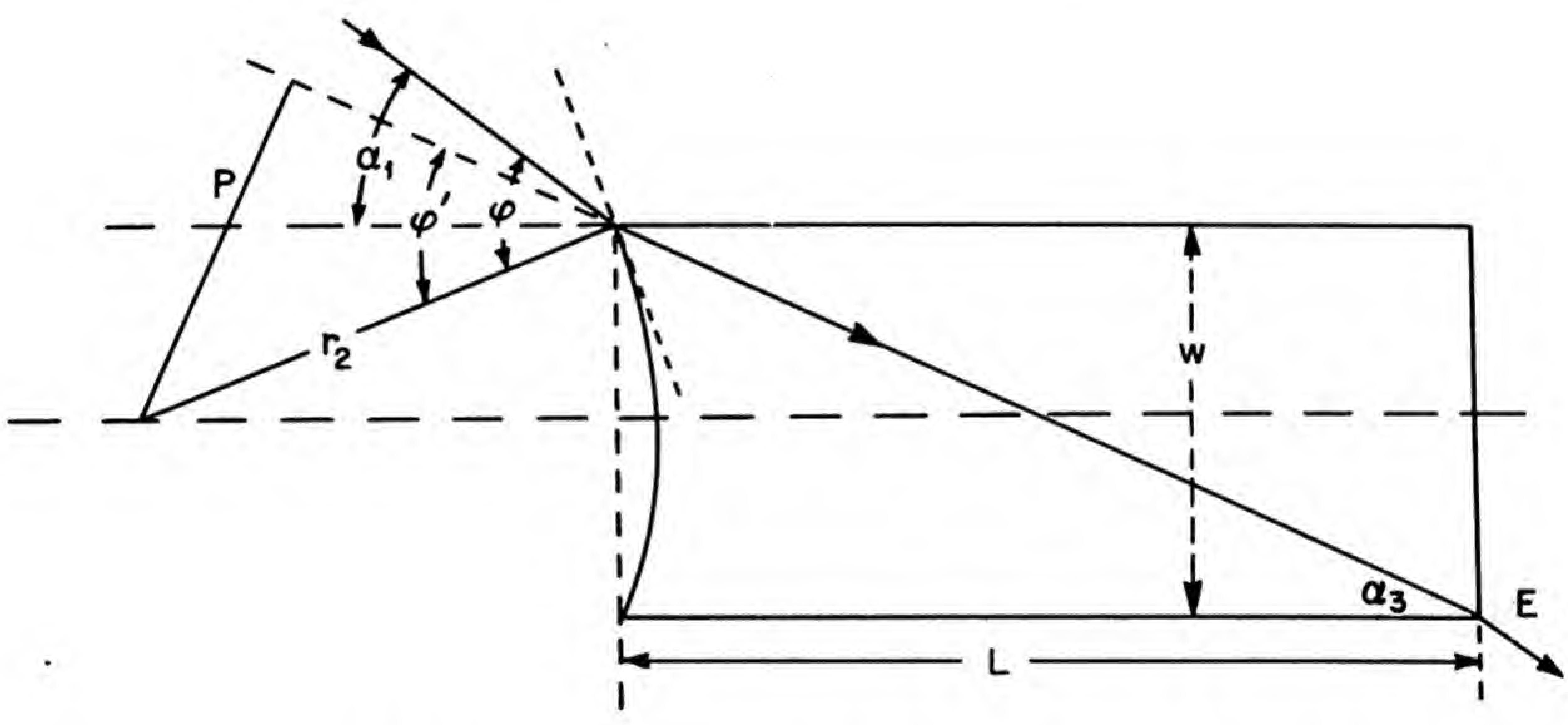


Fig. 2.3—Diagram illustrating angle and distance relations in a liquid-filled tank viewer with a curved window on front surface.

To determine the maximum angle of incidence possible for a window of radius r_2, a ray incident at full height w/2, which, after refraction, leaves the tank at the point E, is again considered. The angle the ray makes with the optical axis before refraction is α_1, and the angle it makes with the axis after refraction is α_3. By geometry

$$\alpha_3 = \alpha_1 + \varphi' - \varphi \tag{12}$$

where φ is the angle the incident ray makes with the normal to the surface and, similarly, φ' is the angle the refracted ray makes with the normal. (The sign convention for the angles described in Sec. 2.1

holds here, where, instead of the optical axis, the normal is considered the axis.) It may be shown that

$$\sin \varphi = \frac{n_3 P}{n_1 r_2} \tag{13}$$

$$\sin \varphi' = \frac{P}{n_1 r_2} \tag{14}$$

where P is the normal from the center of curvature of the surface to the refracted ray. The quantity P may be determined from Fig. 2.3 because

$$\frac{P}{-r_2 + \frac{L}{2} - |\sigma|} = -\sin \alpha_3 = \frac{w}{\sqrt{w^2 + L^2}}$$

and

$$P = \frac{w\left(\frac{L}{2} - r - |\sigma|\right)}{\sqrt{w^2 + L^2}} \tag{15}$$

From this it follows that

$$\alpha_1 = -\tan^{-1}\frac{w}{L} + \sin^{-1}\frac{n_3 w\left(\frac{L}{2} - r - |\sigma|\right)}{r\sqrt{w^2 + L^2}} - \frac{\sin^{-1} w\left(\frac{L}{2} - r - |\sigma|\right)}{r\sqrt{w^2 + L^2}} \tag{16}$$

where $|\sigma|$ is defined as

$$|\sigma| = |r| - \frac{\sqrt{4r^2 - w^2}}{2} \tag{17}$$

It may be seen from Eq. 16 that for given values of w, L, and n_3 the absolute value of the incident angle α_1 increases with decreasing values of $|r|$ to the limiting value. (This limiting value will be discussed later.)

In order to determine the dependence of the value of α_1 upon the other variables, it is best to consider a first-order approximation to Eq. 16. That is, allow $\sin \alpha = \tan \alpha = \alpha$. This approximation will not hold for large values of α_1, but at the moment interest is not in the

exact values of α_1 but in the trend of its value for varying values of w, L, n_3, etc.

The following recursion formulas will be used without derivation:

$$n_{i+1}\alpha_{i+1} = n_{i+1}\alpha_{i+1} d_i h_i \tag{18}$$

$$h_{i+1} = h_{i-1} - \delta_i n_i \alpha_i \tag{19}$$

where h_i is the height of the ray upon the *ith* surface, $\delta_i = t_i/n_i$ (where t_i is the thickness of the *ith* medium), and d_i (the power of the surface) is defined as

$$d_i = \frac{n_{i+1} - n_{i-1}}{r_i} \tag{20}$$

It follows from Eqs. 18 and 20 that

$$n_1\alpha_1 = n_3\alpha_3 + \frac{n_3 - n_1}{r_2} h_2$$

or

$$n_1\alpha_1 = -n_3 \frac{w}{L} + \frac{n_3 - n_1}{r_2} \frac{w}{2} \tag{21}$$

where again the ray from an object strikes the surface at full height w/2.

It may be seen from Eq. 21 that the absolute value of α_1 will increase with increasing values of the ratio of tank width to tank length, with increasing index of refraction of the liquid, and with decreasing values of the absolute value of r_2.

As in case 1, much can be learned abcut practical dimensions for such a tank by considering the magnification and the limiting value of the incident angle as determined by the critical angle. As stated before, the geometric magnification is equal to $\tan \theta'/\tan \theta$.

To determine the critical angle, the angle of incidence φ is considered (see Fig. 2.4). If a ray is to be refracted, the angle φ' which it forms with the normal to the surface cannot have a sine value greater than 1.

From Eqs. 13 and 15 it is seen that the limiting value is given by

$$n_3 w \frac{\left(\frac{L}{2} - r - |\sigma|\right)}{n_1 r_2 \sqrt{w^2 + L^2}} = 1 \tag{22}$$

If four of the values are known, the limiting value of the fifth may be determined by Eq. 22.

Again consider a tank 48 in. long, 18 in. wide, and filled with water of index 1.33, for an object in air.

Substituting these values in Eq. 22, it is seen that $r > 19.09$. By substituting different values of r in Eq. 22, the corresponding maxi-

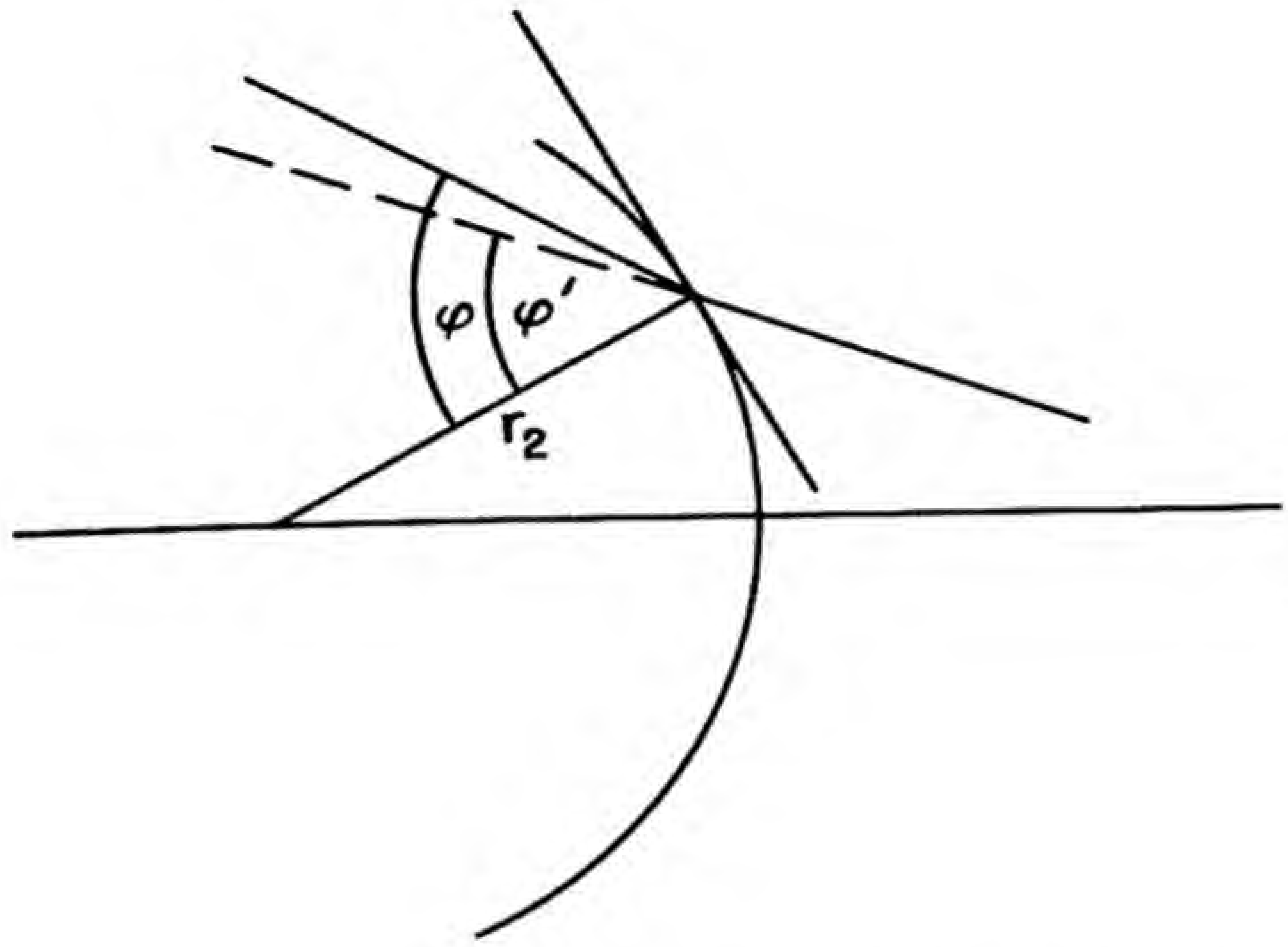


Fig. 2.4—Diagram illustrating the angle of incidence.

Table 2.1—Angles of View and Corresponding Magnification*

r_2	φ' (max.), deg	$M = \dfrac{\tan \theta'}{\tan \theta}$
−19.09	−59.27	0.730
−20.0	−50.89	0.754
−22.0	−45.14	0.784
−25.0	−41.02	0.824
−30.0	−37.54	

*For a tank 18 in. in diameter, 48 in. long, filled with water of index 1.33, for object in air.

mum angles of view are found, and from Eqs. 7 to 11 the magnification is found (see Table 2.1). The angles of view and the magnifications for the different cases are compared in Figs. 2.5 and 2.6.

2.4 Case 3: Window of Same Thickness. The tank viewer may be further elaborated by the placement of a negative lens in front of, and in contact with, the liquid. The total effect then is that of a doublet

with a negative focal length. A plano-concave, double-concave, or negative meniscus could be used as a first element. The plano-concave lens with an auxiliary tank will be discussed in detail (see

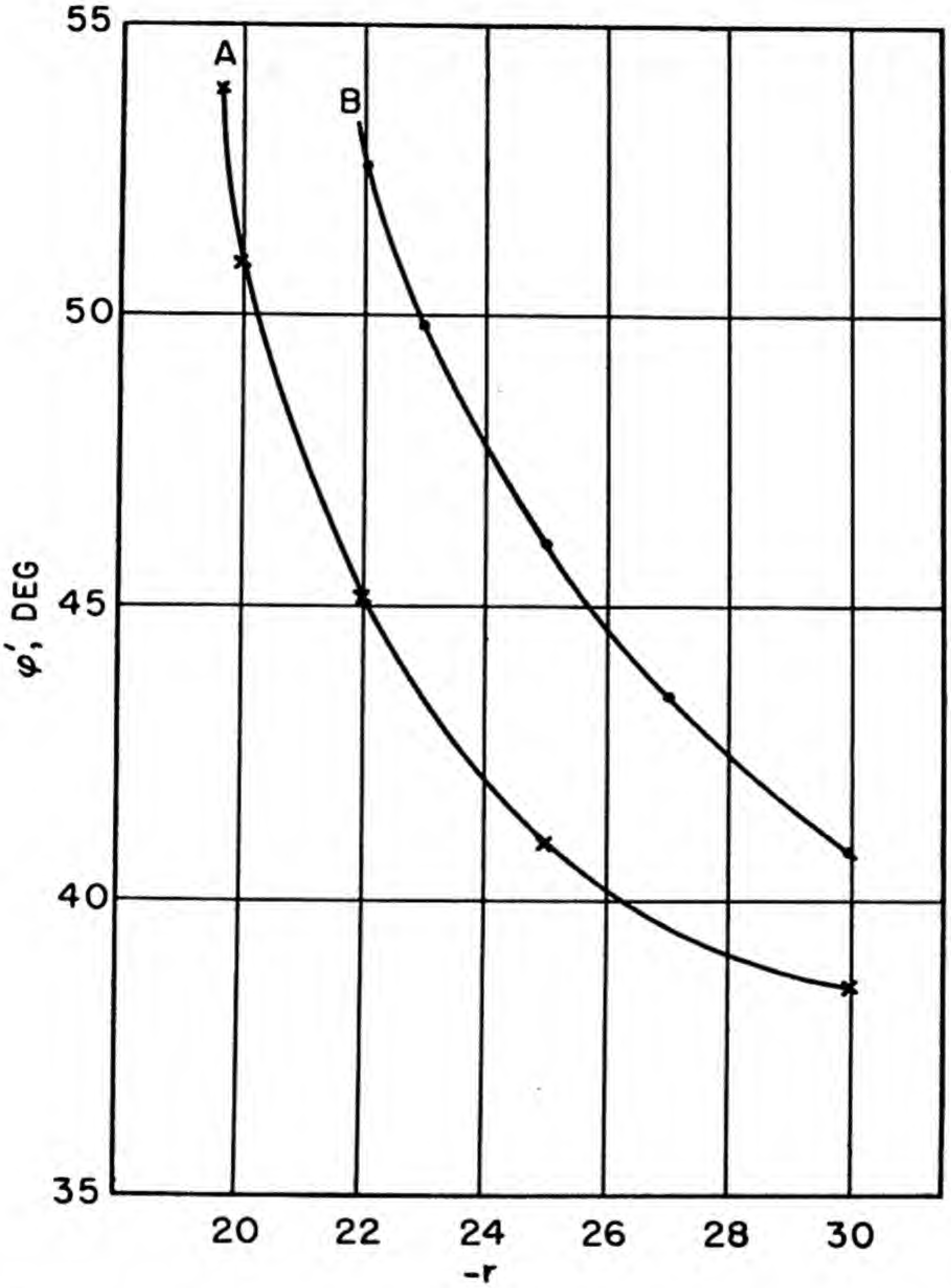


Fig. 2.5—Graph giving comparison of angle of view with values of r for two different indices.

Fig. 2.7). One equation for the exact angle of view is fairly impossible to obtain for this case. However, the first-order approximation to this angle will indicate trends, etc.

As stated before,

$$d_2 = \frac{n_3 - n_1}{r_2}$$

$$d_4 = \frac{n_5 - n_3}{r_2} = 0$$

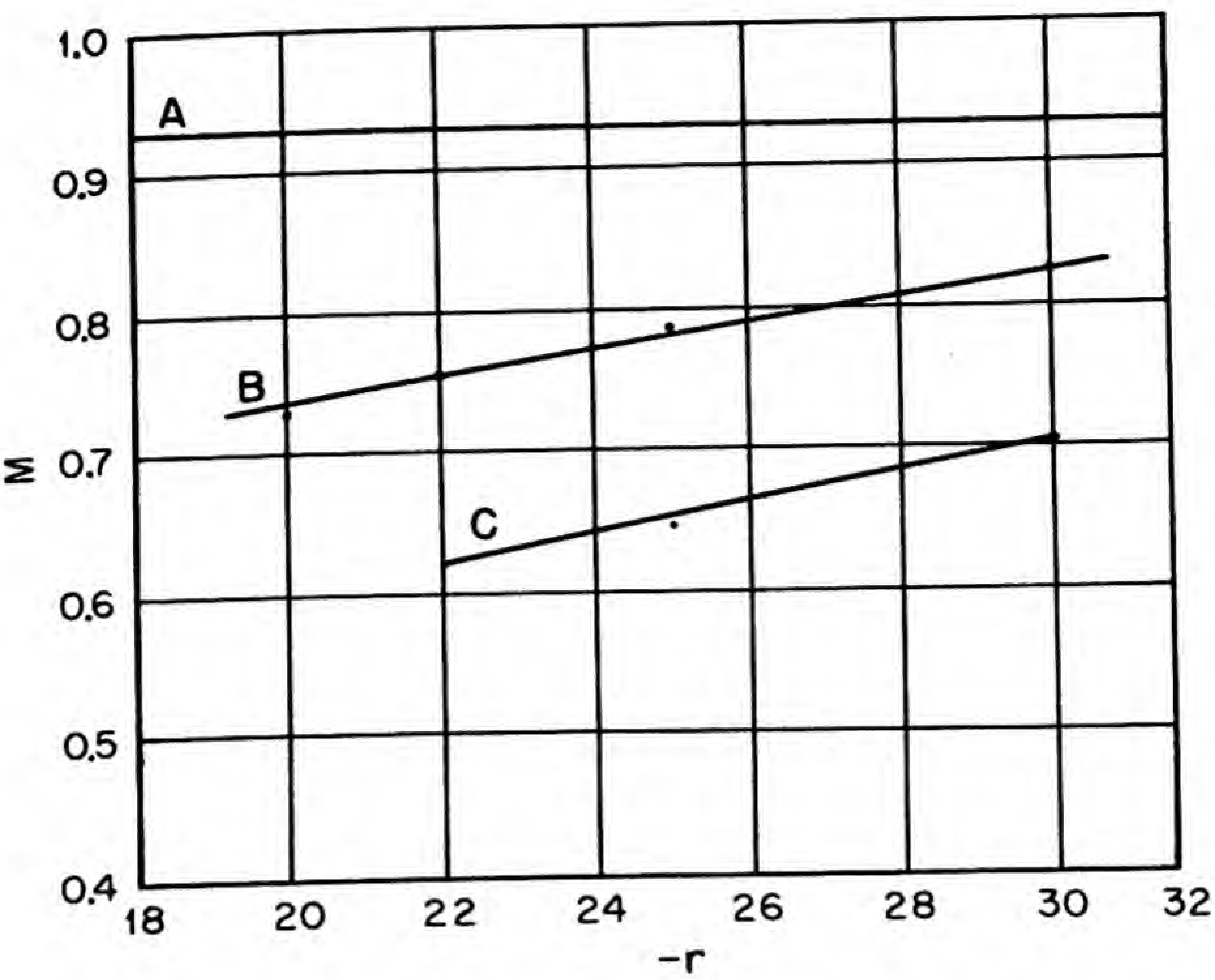


Fig. 2.6—Graph giving comparison of angle of view with magnification for three different indices.

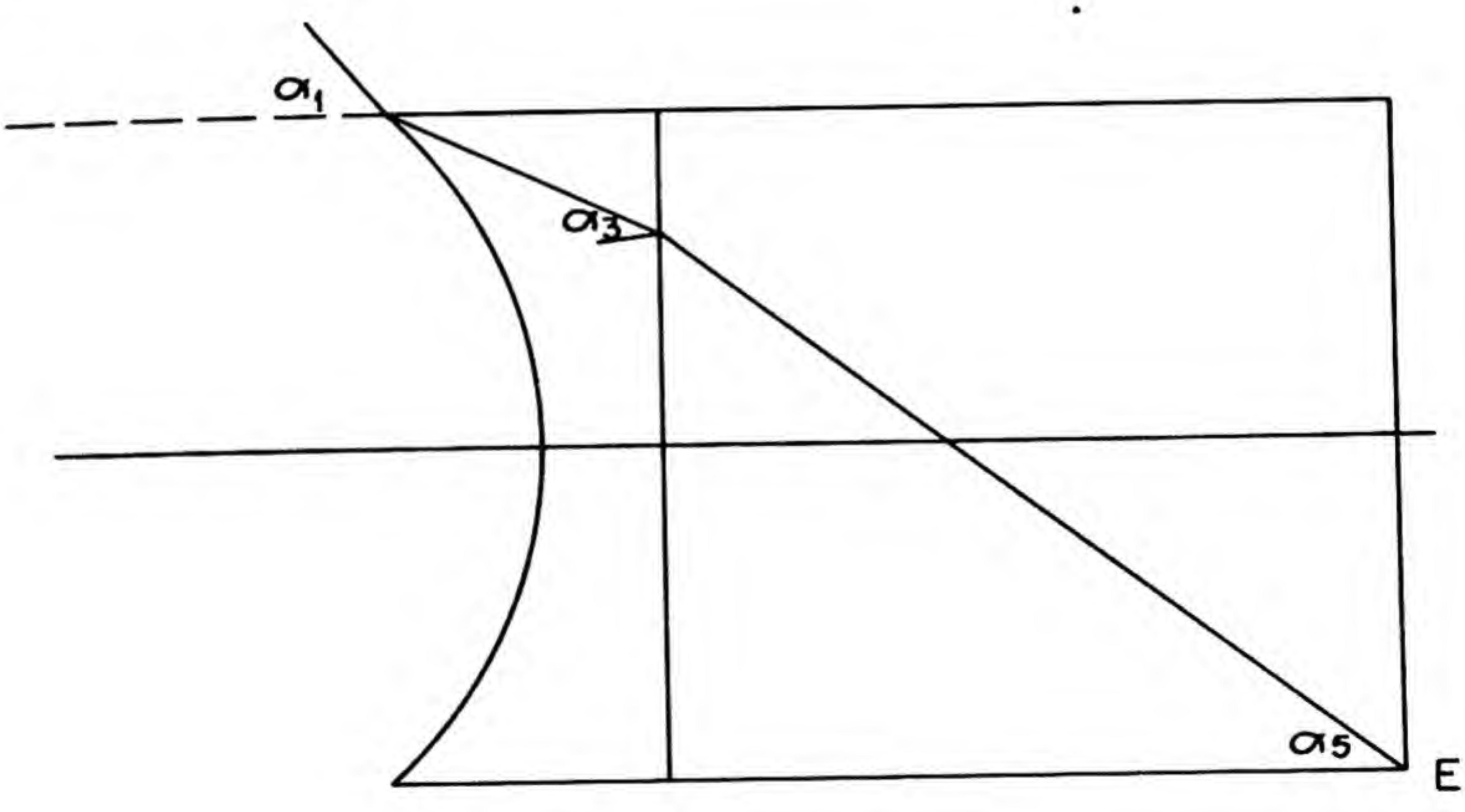


Fig. 2.7—Plano-concave lens window.

Therefore the total power of the system is equal to d_2.

By combining the recursion formulas with the foregoing values of d_i, it can be shown that

$$\frac{-w}{\frac{t_3}{n_3}+\frac{t_5}{n_5}} + \frac{n_3 - n_1}{r_2} h_2 = n_1\alpha_1$$

Substituting w/2 for h_2, and L for t_5, it is seen that

$$\frac{-w}{\frac{t_3}{n_3}+\frac{L}{n_5}} + \frac{n_3 - n_1}{r_2}\left(\frac{w}{2}\right) = n_1\alpha_1 \tag{23}$$

It is seen that $|\alpha_1|$ will increase with increasing values of $w/(L + t)$, with increasing values of $(n_3 - n_1)$, and with decreasing values of $|r_2|$. As before, the limiting value for α_1 is the critical angle. However, in this case there is no exact equation for α_c. The limiting value of α_1 cannot be determined by a first-order approximation because, according to the above equations, the following must hold: $\alpha_1 = \sin\alpha_1$.

But for values of $\sin\alpha_1$ close to 1, the approximation $\alpha_1 = \sin\alpha_1$ will not hold. Therefore the limiting value of α_1 will have to be found by other means. As stated before, Eq. 23 can give only a rough idea of α_1 as a function of the constants of the system.

A special case of a plano-concave lens in front of a liquid-filled tank will tell much about the scheme. Again, let the tank be 48 in. long, 18 in. in diameter, and filled with water of index 1.33. In front of this tank is a polystyrene lens of index 1.5912 and with an edge thickness of 3.5 in. (see Fig. 2.8).

If a ray is considered entering the lens at full height w/2 and leaving at point E, from Fig. 2.8 it is seen that

$$h_4 = \frac{w}{2} - t_3 \tan\alpha_3 \tag{24}$$

Also

$$h_4 = \frac{w}{2} - L \tan\alpha_5 \tag{25}$$

and

$$n_3 \sin\alpha_3 = n_5 \sin\alpha_5 \tag{26}$$

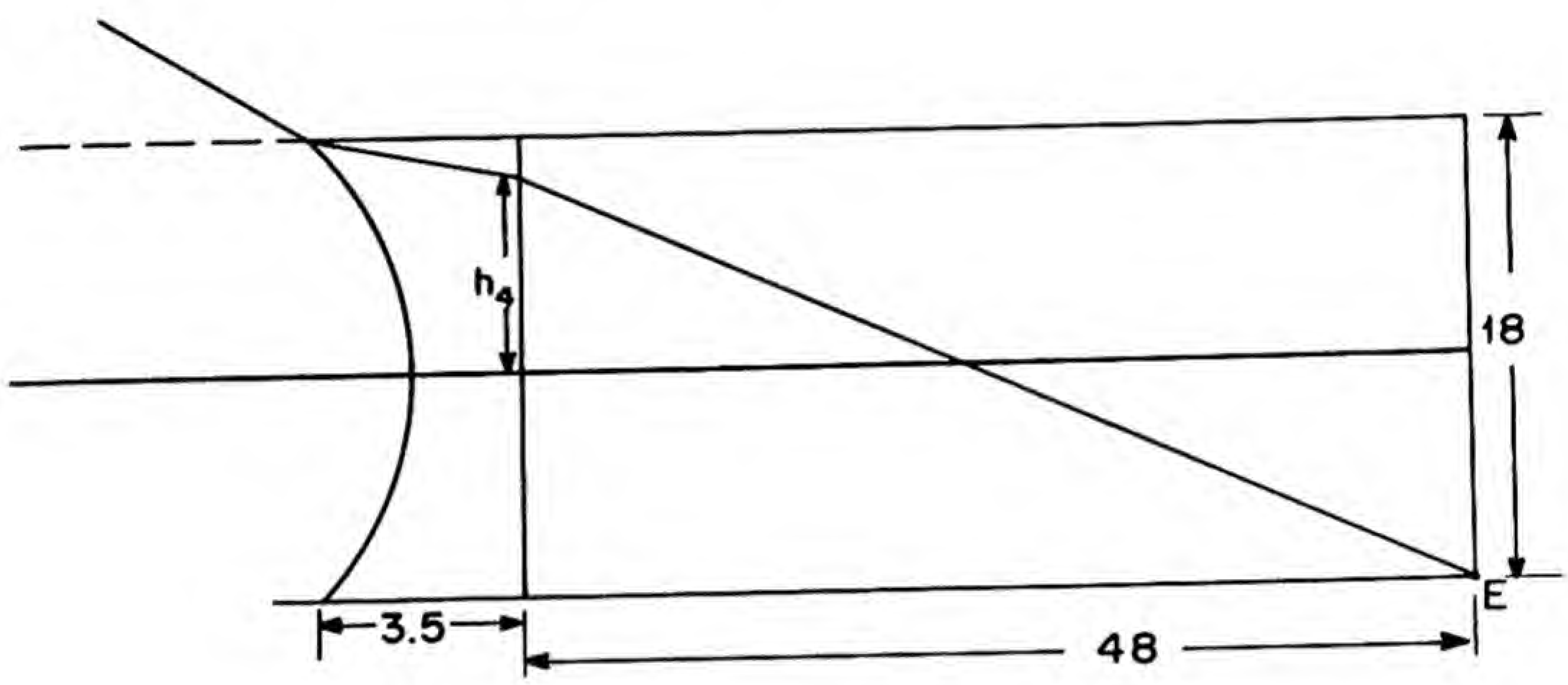
There is only one value of α_3 and α_5 which will satisfy these equations for given values of w, L, n_3, and n_5. By combining Eqs. 24 and 25, the following is obtained:

$$t_3 \tan \alpha_3 + L \tan \alpha_5 = -w \tag{27}$$

If

$$t \tan \alpha_3 + L \tan \alpha_5 = S$$

and the graph of S is plotted against α_3 for assigned values of tan α_3 and corresponding values of tan α_5 (from Eq. 26), that value of α_3 for



NOTE: DIMENSIONS ARE IN INCHES

Fig. 2.8—Plano-concave lens in front of a liquid-filled tank.

which S = −w can be read from the graph. This will give the maximum α_3, and from this α_1 (max.) may be found for different values of r (see Fig. 2.9).

As in case 2, the limiting value of α_1 may be found by setting sin $\varphi = -1$ and solving for r. This value of r will be the minimum r usable.

From Fig. 2.10 it is seen that

$$P = (a' - r - |\sigma|) \sin \alpha_3$$

where a′ is the distance from the last surface of the lens to the point at which the ray at angle α_3 crosses the optical axis. Sin α_3 has been determined and is equal to 0.2788 (Fig. 2.9). From the preceding equations may be written

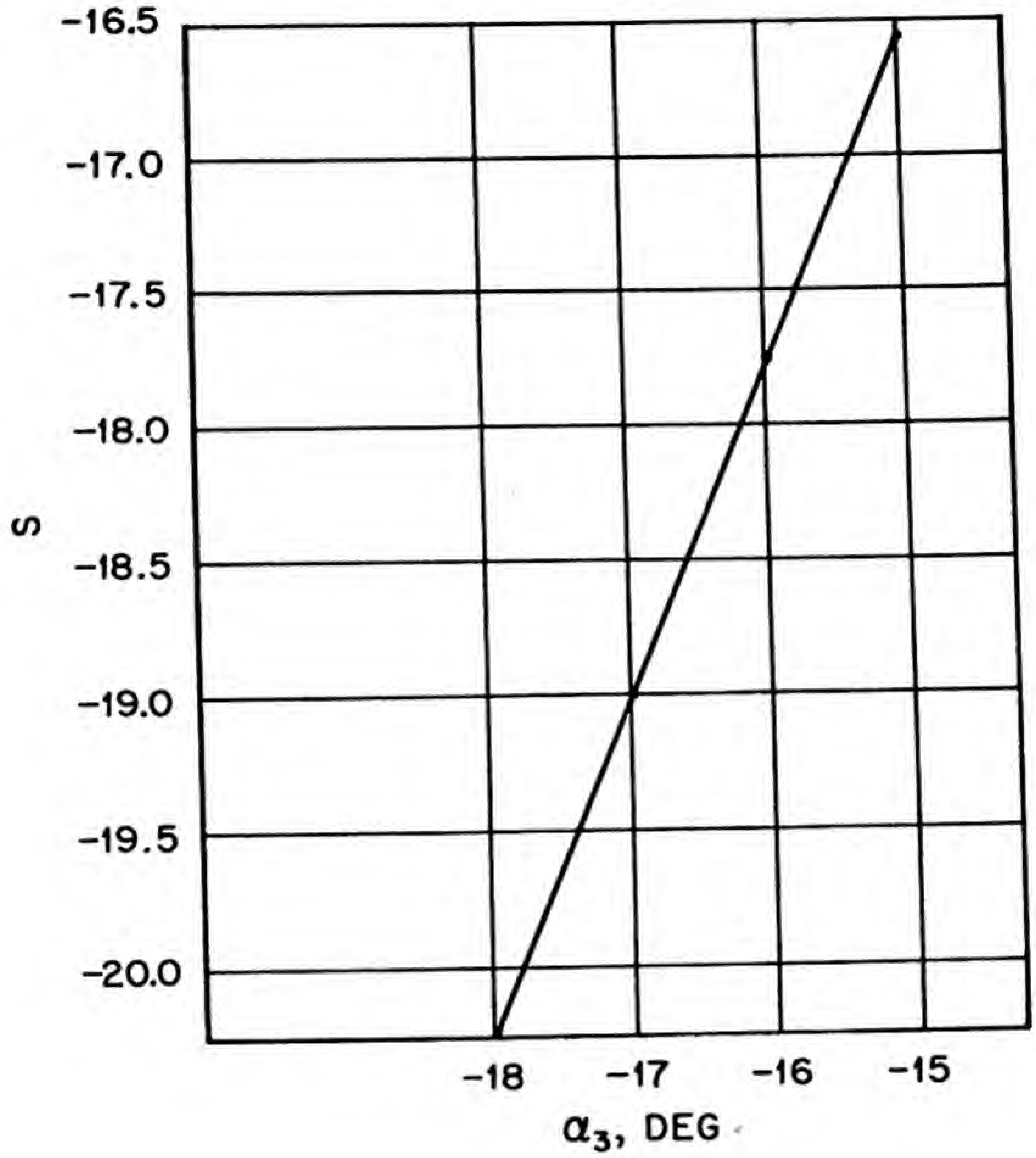


Fig. 2.9—Graph of S versus α_3.

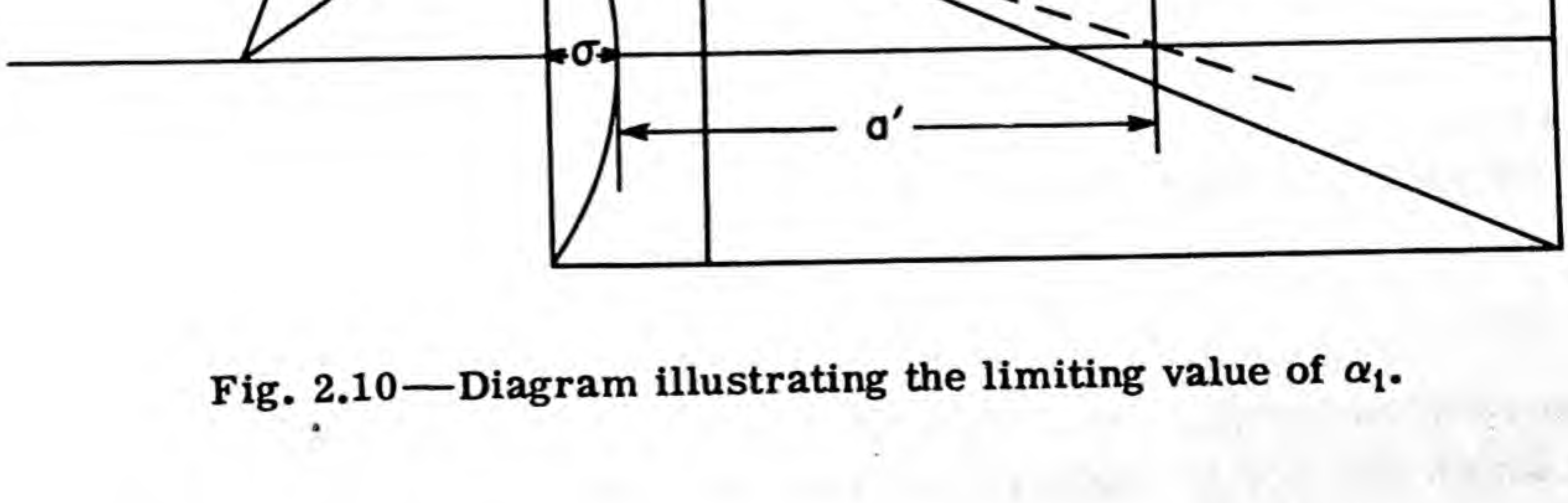


Fig. 2.10—Diagram illustrating the limiting value of α_1.

$$\sin \varphi = \frac{1.5912 \left(27.50 + \frac{\sqrt{r_2^2 + 324}}{2}\right) 0.2788}{r_2} = -1$$

Solving this, it is found that r = 22.54.

The values of α_1 obtainable for different values of r are shown in Table 2.2, together with the geometric magnification.

Table 2.2—Values of α_1 for Different Values of r

r, in.	α_1 (max.), deg	M
22	−52.73	0.620
25	−46.07	0.648
27	−43.51	
30	−40.84	0.704

It is seen from Fig. 2.5 that, for a given value of r, a much larger angle of view is obtainable with the polystyrene lens in front of the water tank. But it can be seen from Fig. 2.6 that, for a given r, the magnification is smaller for the tank with a polystyrene lens in front. It is possible to substitute a double-concave lens for the plano-concave type and thus obtain an equally high power with longer radii.

For a plano-concave lens of given radius and index

$$D = \frac{n_3 - n_1}{r_2}$$

For a double-concave lens

$$D = \frac{n_3 - n_1}{r_2} + \frac{n_5 - n_3}{r_4} - \frac{t_3}{n_3} \frac{n_3 - n_1}{r_2} \frac{n_5 - n_3}{r_4} \tag{28}$$

Thus a given power can be obtained in a double-concave lens of longer radii.

A meniscus-type lens could also be used in front of the tank. In order to obtain a high power in this scheme, a liquid of high index would be desired. That is, in Eq. 28 it would be desirable to have n_5 greater than n_3 for a large angle of view. It should be possible by using either of these lenses to design a well-corrected tank viewer with a large angle of view.

2.5 Application to Project Problems. Viewing tanks were needed to view the discharge area of a pile.[4,5] The type of lens used was not designed explicitly for use with a liquid-filled tank, but it was used because a great many of them were immediately available. These lenses, originally designed for use in airplanes, consist of two negative lenses separated by an air gap (see Fig. 2.11).

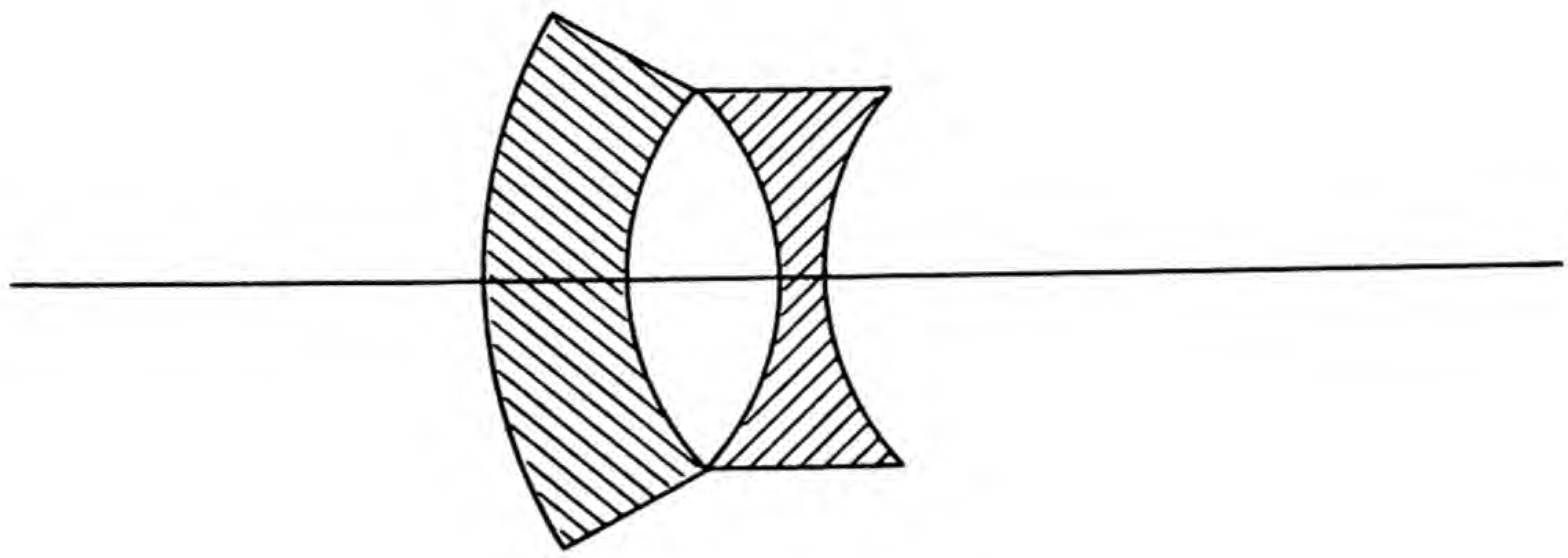


Fig. 2.11—Two negative lenses separated by air gap.

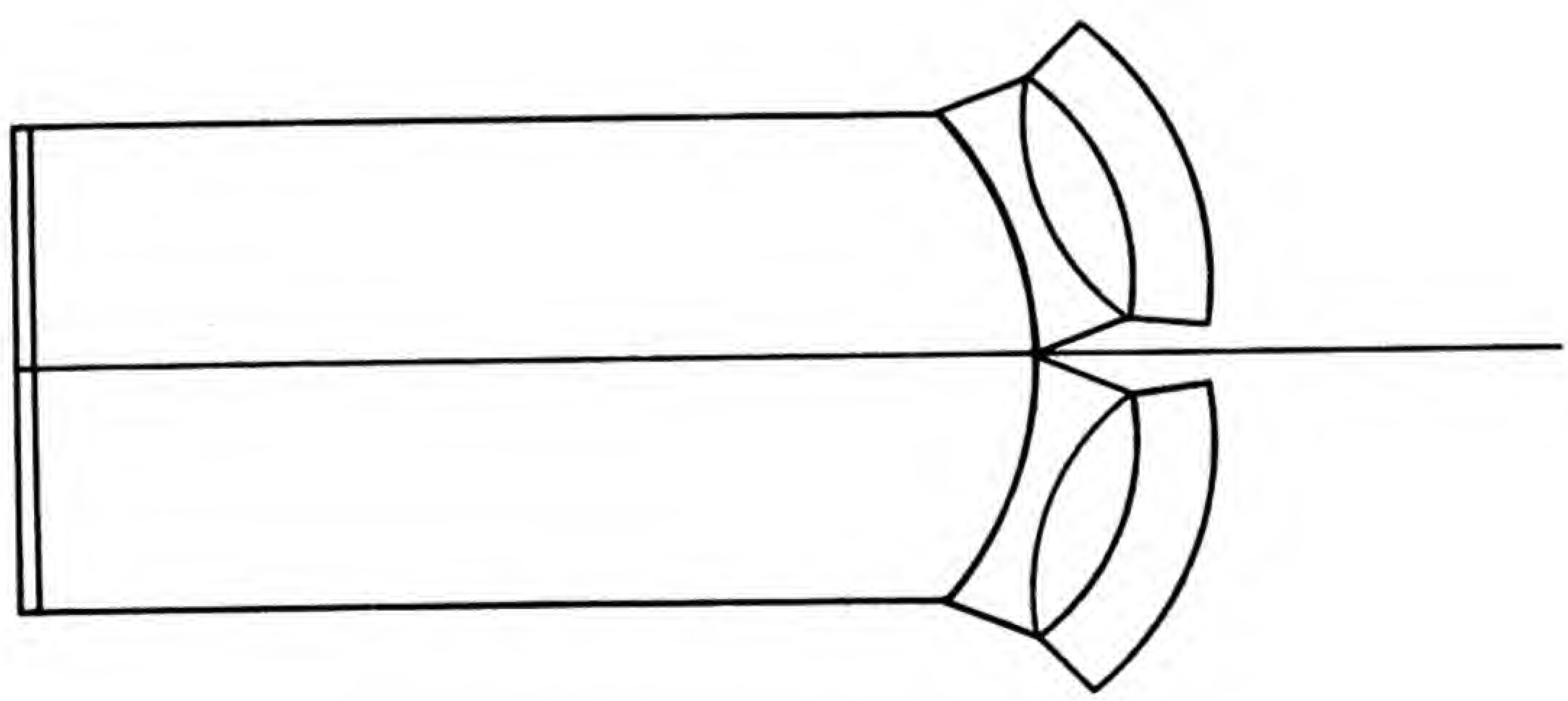


Fig. 2.12—Fly-eye.

When used in air without an auxiliary tank, this lens has an angle of view of 183 deg. To make possible the viewing of a larger area, the fly-eye was built[6] (see Fig. 2.12). The fly-eye is a large liquid-filled tank with four airplane lenses placed at angles in the front in order that all four rear faces are on a portion of a common sphere.

The lenses are placed at an angle of 20°36′ with the axis of a tank 3 ft in diameter filled with water of n_D equal to 1.33. The over-all

length of the viewer is then 7 ft 6 in. The front of the instrument is 11 ft 9 in. and is ⅛ in. from the pile face. It is placed so that its center point coincides horizontally with the vertical center line of the pile face and is 3 ft below the center of the pile face. Each lens of the tank affords a view about 11 ft in diameter.

Similar results could have been obtained had one large lens been placed in front of this large tank. As mentioned before, the airplane lenses were used because their immediate availability overshadowed the drawbacks of their design.

3. MIRRORS

One of the simplest ways of looking into a forbidden area is by means of large mirrors. In a sense a mirror system is a "lens-free" periscope. The principal objection is the difficulty of getting large mirrors sufficiently free from surface irregularities. Mirrors have an advantage in that only a portion of the mirror is used for a given object point since the cone of rays is limited by the pupil of the eye. If, however, an auxiliary instrument such as a telescope is used, the entrance pupil is no longer the pupil of the eye but the much larger telescope objective. All mirror surfaces must be extremely flat if definition is to remain good. Mirrors must be kept clean and free from dust. If the right number of mirrors is not used, the image will not be erect or right-side-to. In periscopes, design can always provide for erection of the image.

Moreover, the reflecting power of a single mirror is rarely above 75 per cent after a period of use, and the reflecting power of two or more mirrors is much less. With modern low-reflection coating methods and wide-aperture optical design, almost any periscope can be expected to have a transmission of approximately 40 per cent or better.

Another disadvantage of a mirror system as contrasted with a periscope is that the latter may be made very small in diameter compared to its length. Mirror systems require very large openings or labyrinths.

One periscopic instrument built by the section has an over-all diameter of 1⅜ in. and a length of 46 ft. Theoretically, it could be several times as long. The angle of view of this instrument is about 20 deg, and it could be made to scan a solid angle of about 3π. A mirror system of the same limited cross section would have an angle of view of about 7 min of arc. A similar comparison should be made for a periscope of less extreme dimensions. A common type is 4 in. in diameter and 12 ft long with a field of view of 24 deg. The angle of view of an equivalent mirror system would be about 50 min of arc.

4. TELESCOPES

The telescope is used for one or both of two purposes: (1) to obtain a magnified image of a distant object and (2) to gather more light than reaches the unaided eye. The primary optical need in the Project is for means to look about and inspect the inside of a space surrounded by a biological shield. High magnification is of secondary importance, and light is not at a premium. If its magnifying power is great, its field is correspondingly limited. It gives an inverted image. Reinversion of the image can be achieved by an erecting eyepiece, but this is not always light efficient. Moreover, if additional optical parts are to be included, it is better to abandon the telescope completely and to use a design more fundamentally adapted to the job of scanning a large volume of space, the scanning periscope.

Another limitation on the telescope is the excessively large range of motion of the eyepiece required for focusing on nearby objects. This can be avoided in the periscope.

As in the case of the window, the telescope is useful provided there is a need for something for a limited or a single operation only. Also, as in the case of the window, it is better to plan to use standardized periscopic equipment. In this connection, it should be pointed out that in most cases the standard unit parts of a periscope or borescope are actually telescopes.

5. MICROSCOPES[7–9]

A microscope is used to obtain a greatly magnified image of a small object. The object is placed close to the objective in order to make the magnification of the latter as large as possible. This in itself rules out the microscope for most Project purposes.

However, two uses for microscope-type instruments have been developed. One use arose from the need to measure the depths of pits in aluminum slug casings while they rested on the floor of a storage basin beneath 20 ft of water. A microscope was constructed using a 15-in.-focal-length plastic objective and an ordinary Kellner-type eyepiece. The image formed by the objective was projected upward through an air-filled tube to a point about 3 ft above the level of the water, where it was examined with the aid of the eyepiece. The magnification due to the objective was about 17; that due to the eyepiece was about 10. It is questioned whether the image quality obtained would permit very accurate pit depth determinations.

The other use for a microscope-type instrument grew out of the need to examine the interior walls of long aluminum tubes inside re-

actors. The optical need here is similar to that encountered in industrial plants where steam tubes and other tube interiors must be examined. A similar use is the examination of a gun bore. If the tube or bore is not too long, a microscope can be used although it will necessarily be of special design. Much depends upon the diameter of the opening into which the instrument must be inserted. If this is small, the use of a microscope would be difficult. If the optical instrument must contain its own illuminating equipment, a microscope would be still more difficult to use.

6. PERISCOPES[10–12]

The periscope may be described as an instrument in which the general direction of the rays is not in a straight line but is deflected one or more times with the purpose of giving the observer a view from a position in which he cannot put his head. The simplest form would be one or more mirrors. The requirements of brightness, image orientation, size of field, and maneuverability have led observers to think of a periscope as also containing image-forming optical parts.

The preceding definition seemingly excludes instruments known as "scanning sights." These usually have all lenses in a straight line, but they are equipped with a movable prism or mirror mounted in front of the objective. By rotating the entire instrument on its optical axis and also moving the prism or mirror, the operator can survey a large volume of space. These are truly periscopic instruments and in fact are the type of periscope used most in the Project.

The periscope may be thought of not only as an instrument to form an image in the focal plane of the eyepiece but also as one by which an image of the eye is placed in a position of vantage at an otherwise impossible location. For illustration, the axis-bending optical parts may be omitted and only the lens system considered. Referring to Fig. 2.13, suppose vision of a space is required through a tube of length L and diameter D, and, for simplicity, suppose the objects to be distant. Then, with the empty tube only, an eye placed axially at E will have an angle of view D/L. Many different arrangements of lenses in the tube may be considered,[10] but one example will suffice. Suppose that, at distances L/4 from each end, lenses of focal length L/4 are placed in the tube. With the eye on the axis at E, there will be an image of the eye at E′. Also, the angle of view will be increased to 4D/L. These and other comparisons are listed in Table 2.3.

Except for the orientation of the image and the brightness, the lenses are an advantage. The image can be re-erected by optical

means. The brightness loss is not serious in outdoor daylight, and with artificial lighting it can be overcome.

It should be pointed out that the combination of two lenses discussed in Table 2.3 is in reality a unit-power telescope. Their use in a tube of length 4f or greater, with a scanning element at the end of light entry, constitutes a periscope. A drawback to the use of only

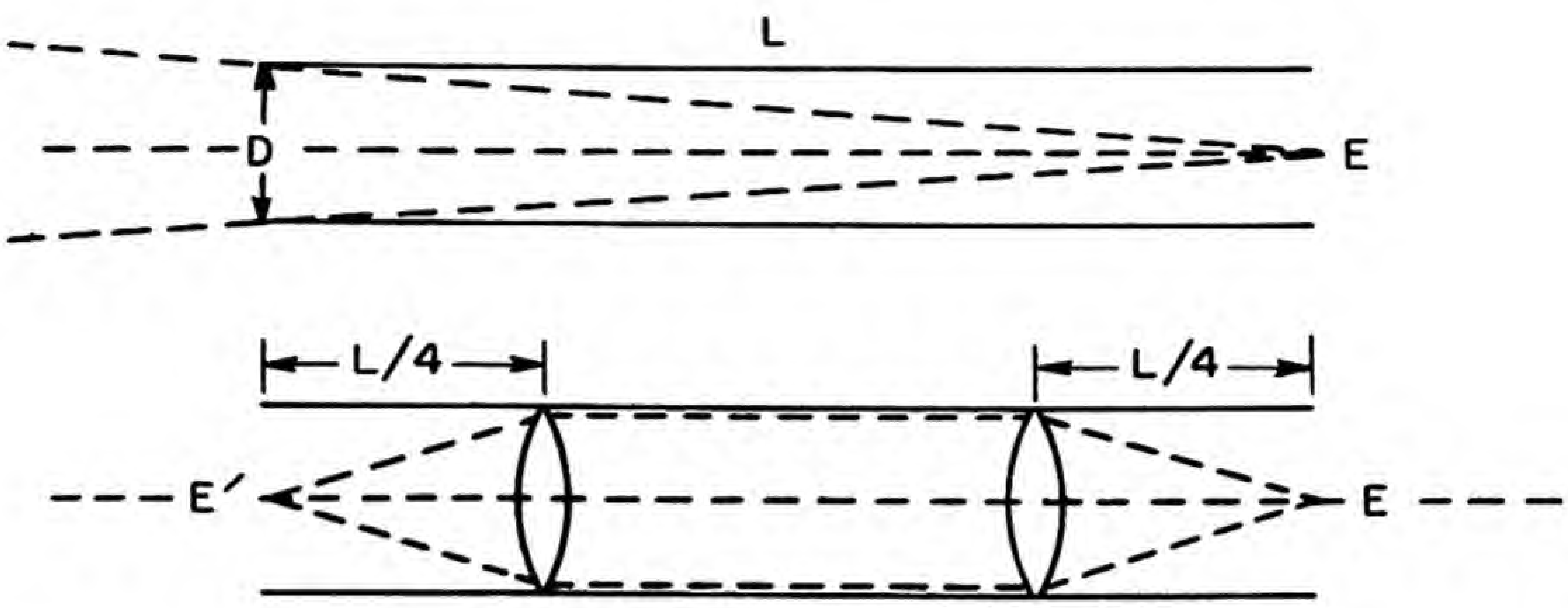


Fig. 2.13—Illustration of the use of lenses to increase the field of view through a long narrow tube.

Table 2.3—Comparison of Empty Tube and Two Lenses in Tube

Optical characteristic	Empty tube	Two lenses (f = L/4) at positions L/4
Field stop	Forward end of tube	Second lens
Field of view	D/L	4D/L
Scanning-element position	E′	E′
Size of scanning element	Oval, width D	Oval, width size of eye pupil
Aperture stop	Eye pupil	Eye pupil
Image	Erect	Inverted
Brightness	Natural	Reduced

two lenses is in the great focusing range required, especially for near objects. This might be overcome by making the first lens of very short focal length in comparison to the second, but this would result in a very small fractional magnification. A better method is to use more lenses in train. The arrangement shown in Fig. 2.14 has many advantages, among which are the following:

1. The use of a short-focus first lens L_1 (the objective) results in a correspondingly small range of position for image I_1 as objects at

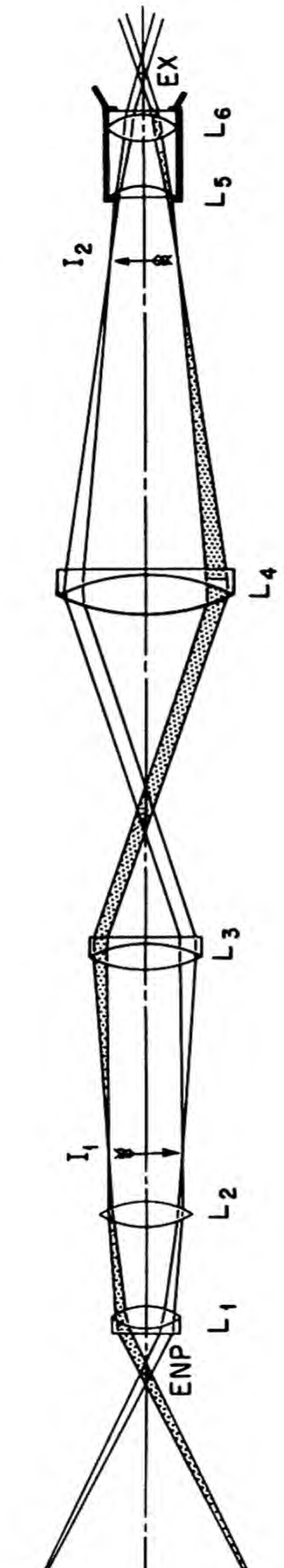


Fig. 2.14—Lens train for use in a periscope.

different distances are viewed. As a result, an eyepiece L_5,L_6 need be moved only through a very short range, even for nearby objects.

2. The small image I_1 permits the use of a small-diameter tube for the fore part of the periscope.

3. The use of a field lens L_2 at, or very near to, I_1 still further constricts the light-ray bundle as far as lens L_3, called the "first erector."

4. If the distance between I_1 and L_3 is the focal length of the latter, rays from any object point are parallel to the right of L_3. Consequently, the remainder of the instrument may be an ordinary telescope. The diameter of its objective, L_4, called the "second erector" of the periscope, should be large enough to receive all the image-forming rays from the object field represented by I_1.

5. The combination L_4,L_5,L_6, constituting a telescope, may be at any appropriate distance from the fore part of the periscope. All that is necessary is that all image-forming rays from L_3 enter L_4. The distance between L_3 and L_4 may even exceed this requirement if it is more expedient to increase the distance at the expense of the field.

6. Transparent materials such as liquids may be put in the optical path between L_3 and L_4 for the purpose of stopping high-intensity radiation. Liquids should be contained in tubes with optically flat windows. If the left face of L_4 and the right face of L_3 are plane surfaces, the lenses may be these windows.

7. Prisms or mirrors may be used either to baffle radiation or to alter the direction of the optical axis for any other reason. In general, prisms should be used only in a region where the rays from any object point are sensibly parallel, as between L_3 and L_4. Otherwise, the spherical aberration due to a thick block of glass will affect image quality. Some chromatic aberration will also result. Mirrors may be used anywhere. The best mirrors have about 88 per cent reflectivity as compared to about 98 per cent transmission for the best prisms.

8. The scanning element, preferably placed at the entrance pupil, ENP, of the system, may be of mirrors or prisms. This will depend on radiation effects and the type of optical engineering required. If a single prism is used, it need be no larger than necessary to encompass the entrance pupil, but a reversion will take place. This may be corrected in one of several ways.

Should it be necessary to increase the length of the periscope and keep the diameter the same, the borescope type of construction may be adopted (see Sec. 7).

The most troublesome case encountered in building periscopes was in the discharge area of a neutron reactor. The most critical conditions of personnel protection are in neutron reactors or in the en-

closure in which they are located. Neutrons are a hazard because of their direct biological effects and also because they induce artificial radioactivity in the materials of which the instrument is constructed. Provision was made for visual examination of the area by having two vertical tubular openings, with offsets in diameter, through the 6-ft-thick concrete ceiling. Into either of these a periscope could be inserted.

Two periscopes were built. One[13] was provided with no protection for personnel other than an offset in the instrument above the ceiling. It could be inserted only when the reactor was shut down. With this periscope it would be impossible to observe in the area except when the reactor was shut down, since to leave the periscope in the tube continuously would induce radioactivity in the lower end and endanger personnel if it were withdrawn for cleaning or servicing. Another objection to its use is the blast of gamma radiation emitted from the opening after the instrument is retracted and before a stopper is inserted, or vice versa. A second periscope[13] was constructed to remain in place continuously. Every effort was made to build into this instrument sufficient shielding and baffling so that the optical parts were protected and so that no radiation could escape above the ceiling. The second of these aims was accomplished. Unfortunately, at the time there was not sufficient knowledge of the degree of protection required to guard against coloration of the lenses and other glass parts. Moreover, there had been no provision made by which sufficient protection could be added to the surroundings of the tube.

7. BORESCOPES

As the name implies, the borescope is an instrument designed to enable an observer to inspect the inside of a narrow tube or bore. The optical train, which is not unlike that of a periscope, can be arranged in two ways, as illustrated in Figs. 2.15 and 2.16. In both, the objective assembly is a short-focus achromat followed by a field lens. Following these, in Fig. 2.15 the lens train consists of image-forming achromats and single-element field lenses placed alternately. The purpose of the field lenses is to bend the rays so as to limit the cross section of the beam without taking part in image formation. These lenses all have the same focal length, and beginning with the field lens of the objective assembly the spacing is twice that of the focal length. A deviation from exactness in this spacing is advisable in the case of the field lenses. If the images formed by the achromats fall too close to the surface of a field lens, defects in that surface or dust on it would appear in the final image. It is better to displace the field

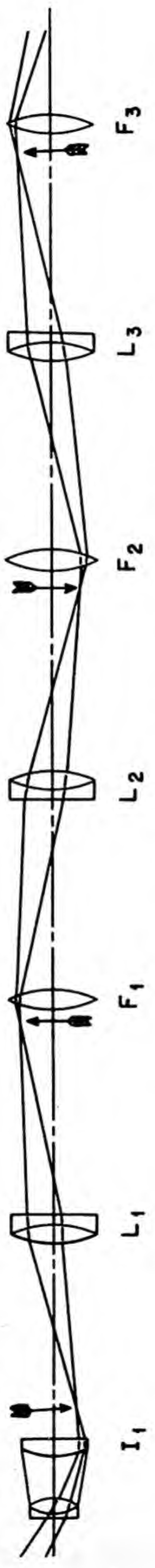


Fig. 2.15—Example of optical train for a borescope.

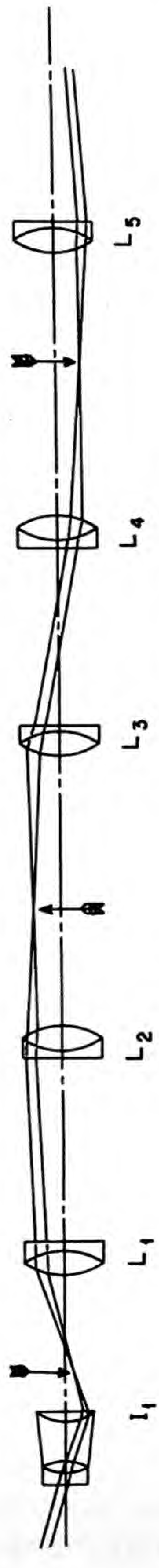


Fig. 2.16—Example of optical train for a borescope.

lenses slightly, but not far enough from the image plane to cause them to have pronounced image-forming functions.

The type shown in Fig. 2.15 gives excellent results and is desirable wherever the entire borescope is in a single unit. It is, however, absolutely inflexible in length. Errors in placing the lenses or variations in their focal lengths result cumulatively in a displacement of the final image position. Sometimes it is desirable to provide a borescope which can be taken apart in short sections. In the Project, damage to any given section might necessitate replacement with a section of identical optical length. The type shown in Fig. 2.16 makes this possible. The objective is placed not at a distance 2f from the first erector L_1 but at a distance such that rays from an object point are parallel between L_1 and L_2, L_3 and L_4, and so on. Should there be slight variations in focal length or focal adjustment, the spacing between any such pair of lenses may be modified to ensure that the final image plane is at an unaltered position.

In the case of the borescopes provided for some reactors, no section could be longer than 8 ft. Accordingly, tubes were made up, each containing four lenses of focal length 12 in., placed 24 in. apart. The positions of the end lenses were adjusted in order that the conjugate image positions were exactly at fiducial marks etched on the outside of the tube.

In the second type every lens except L_2 has image-forming functions and must be a corrected achromat; in the first type alternate lenses are field lenses only and may be simple lenses. It is desirable, however, that in design these be so figured that they take part in the correction of the aberrations in the system.

8. CAMERAS

It was considered desirable to supply a camera with a borescope. When the first borescope was made by the Lenox Instrument Co., a camera attachment was supplied by them. This was a box of fixed length, with a back adaptable for either ground glass or a 3¼- by 4¼-in. film pack. A single achromat lens of about 6 in. focal length is permanently mounted in a tube attached to the box. The camera is used by putting the tube over the eyepiece and focusing the entire instrument until the image appears distinct on the ground glass.

The principal drawback to this camera is that it gives a much magnified image, with consequent loss of speed. For instance, photographs taken in the Chicago laboratory through 40 ft of borescope No. 2 required exposure times of 15 min. Other objections were:

1. The visually focused image did not fall accurately in the film plane.

2. Light was insufficient for visual focusing.

3. The achromatic lens supplied was not of good photographic quality.

It was considered desirable to design a special camera for such use. Later this camera was adapted for use also on the underwater periscope.

In order to shorten exposure times, it was decided to place the photographic film at the final image plane which is viewed through the eyepiece. A number of Perfex 55 cameras were obtained, and a special mounting was constructed, permitting photography of an object field by simply swinging the eyepiece out of, and the camera into, the field of view. The details of the instrument are discussed in Paper 5.3 of this volume.

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Chapter 3

MISCELLANEOUS INSTRUMENTS AND SERVICES OF THE PROJECT OPTICAL SECTION

1. FLUORIMETRY FOR PROJECT PURPOSES

The development of fluorimetry for Project purposes[1–6] has been extensive. The type required depends on the particular problem on hand. In the past, much attention has been given to measurements of fluorescence in solutions, and sufficient discussion of these is to be found in current literature. A more difficult problem optically is the examination of a fluorescent solid.

In general, one optical system must carry the light from the source and distribute it over the sample. Another is needed to collect the fluorescence and concentrate it on the screen of a photocell. The wide angles required impose a need for compactness. The geometry of the two systems must be fitted into a small volume. Newer types of optical design are required, and a few of these are discussed below.

1.1 Transparent Solid or Liquid. For a transparent sample the design shown in Fig. 3.1 is satisfactory. Light from S passes through the adjustable aperture A, lens system L_1L_2, and ultraviolet-light-transmitting filter F_1 to the sample U. There the emitted light passes through the ultraviolet-absorbing filter F_2 to the photocell P, which is connected to an amplifying circuit. The aperture A is placed at the entrance pupil of the system L_1L_2 in order that a decrease in the size of the opening will diminish the amount of light passed without affecting the image size. If the aperture opening is calibrated against different standards, then fluorescence may be measured by the amount of opening necessary to produce a given response of the photocell.

1.2 Opaque Solid (Finely Ground). Because fluorescence is not influenced by the angle of the incident light, this light may strike at a glancing angle. If the sample is in a powdered form, there will be no reflection of the exciting light. There are a few possible ways of getting the ultraviolet light onto the photocell in a very small distance.

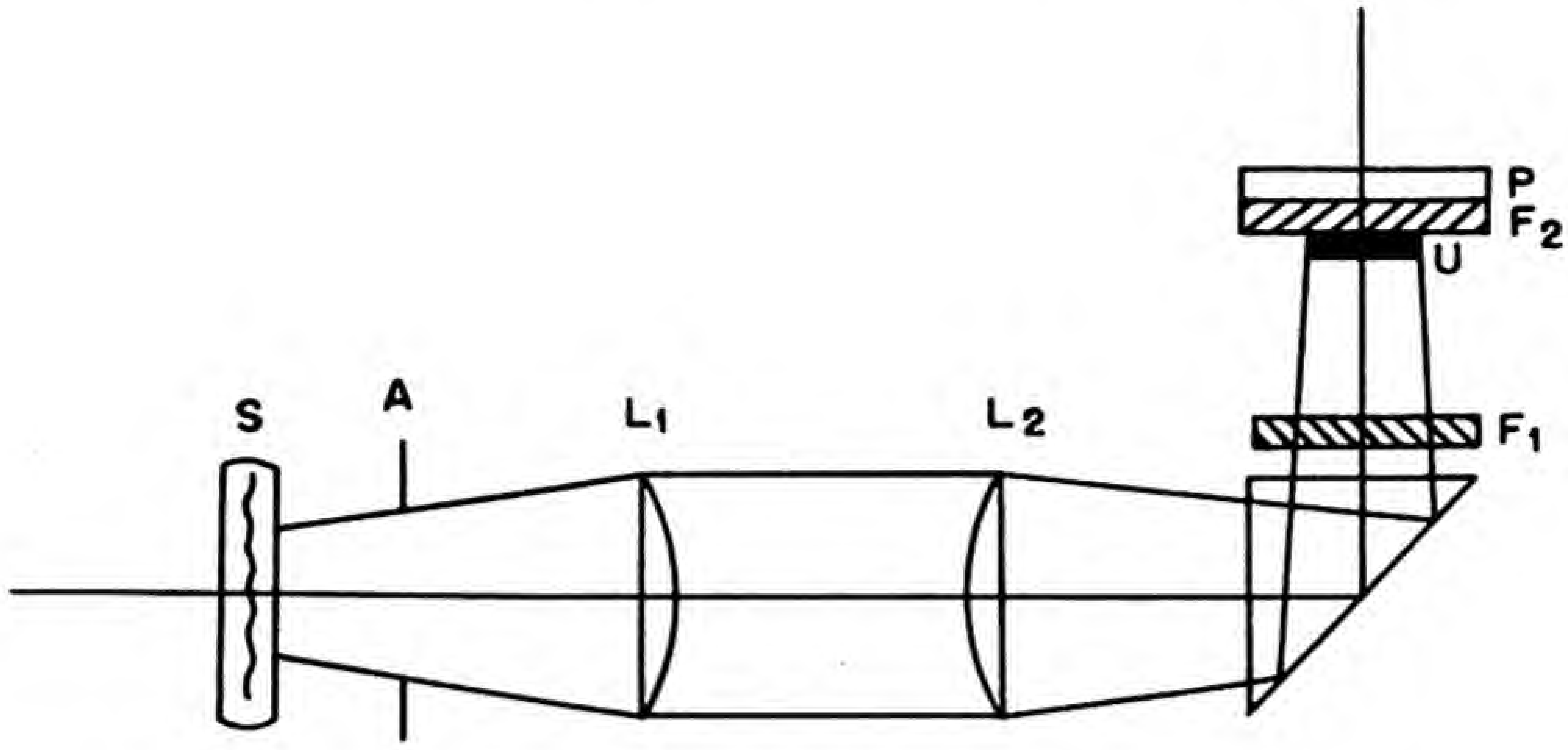


Fig. 3.1—Lens system for viewing a transparent sample.

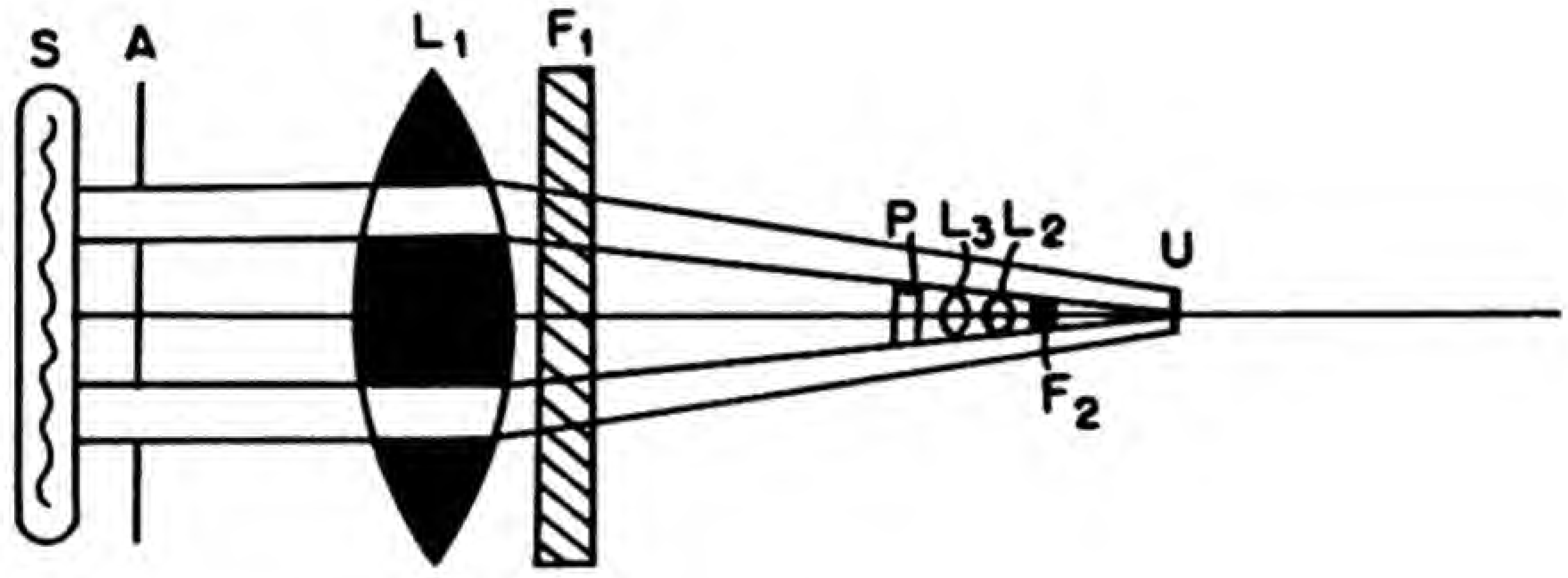


Fig. 3.2—Doughnut-shaped aperture system.

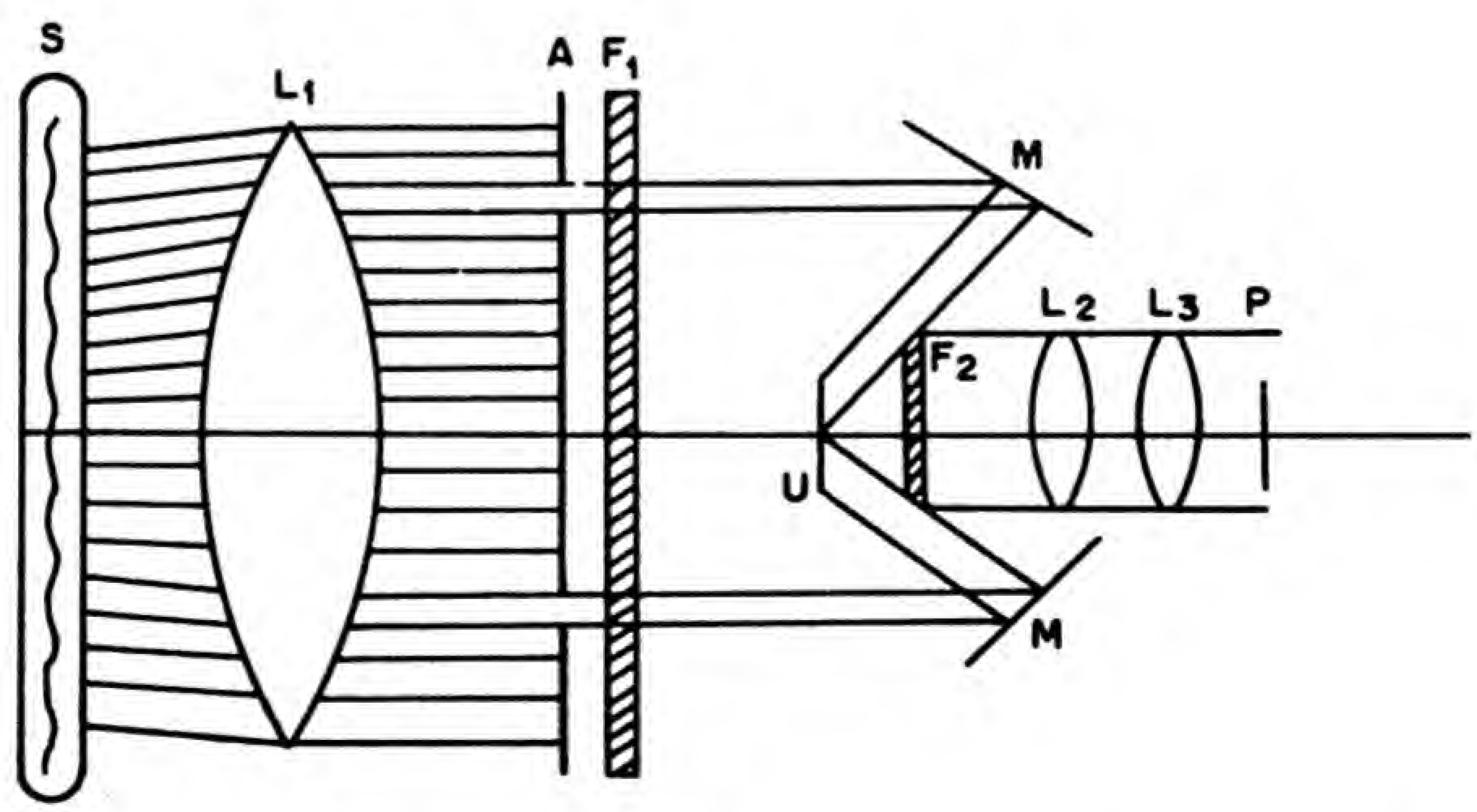


Fig. 3.3—Mirror system for viewing an opaque solid.

(a) Doughnut-shaped Aperture. A doughnut-shaped aperture system is shown in Fig. 3.2. Lens L_1 is painted in order that light passes only through a doughnut-shaped portion of it. Light from S passes through aperture A, lens L_1, and ultraviolet-light-transmitting filter F_1 to sample U. There emitted light passes through ultraviolet-light-absorbing filter F_2 and lens system L_2L_3 to photocell P. Aperture A may be adjustable.

(b) Mirror System. Figure 3.3 shows a mirror system for viewing an opaque solid. Again, light from S passes through lens L_1, aperture A, and filter F_1 to conical mirror M. The reflected beam strikes the sample U, and the light emitted from U passes through filter F_2 and lens system L_2L_3 to photocell P.

(c) Plastic Rods. In this system (see Fig. 3.4) the exciting light is carried to the sample through rods transparent to the ultraviolet. (This has not been investigated thoroughly; consequently the proper material for this purpose is not known.) Such a system, however, would have the advantage of not requiring auxiliary lens systems. Four rods would probably be satisfactory although another number could be used. Light from sources S passes through rods R and filters F_1 to the sample U. Light from U passes through filter F_2 to photocell P.

(d) Incident Light at Large Glancing Angle. In this system (see Fig. 3.5), light from a lens system strikes the sample at a large angle, and the emitted light passes through another lens system to the photocell.

This type of fluorimeter has been investigated, and the following lenses, etc. (see Fig. 3.6), are recommended for such an instrument:

Lens	Thickness, cm	Diameter, cm	F.L., cm	Type
L_1	1.8	7.7	8.2	Plano-convex
L_2	1.8	7.7	8.5	Plano-convex
L_3	1.2	5.1	6.5	Plano-convex

The image formed on the screen is oval in shape, with the long diameter 3.8 cm and the short diameter 2.2 cm. To determine the proper lens system for carrying the light from a fluorescent source of this size to a photocell (see Fig. 3.7), a light was placed behind a diaphragm of those dimensions, and the light was made to focus on a screen 1 by $^{11}/_{32}$ in. (the size of the light-receiving screen of the photocell). The following lenses, etc., are recommended for this system:

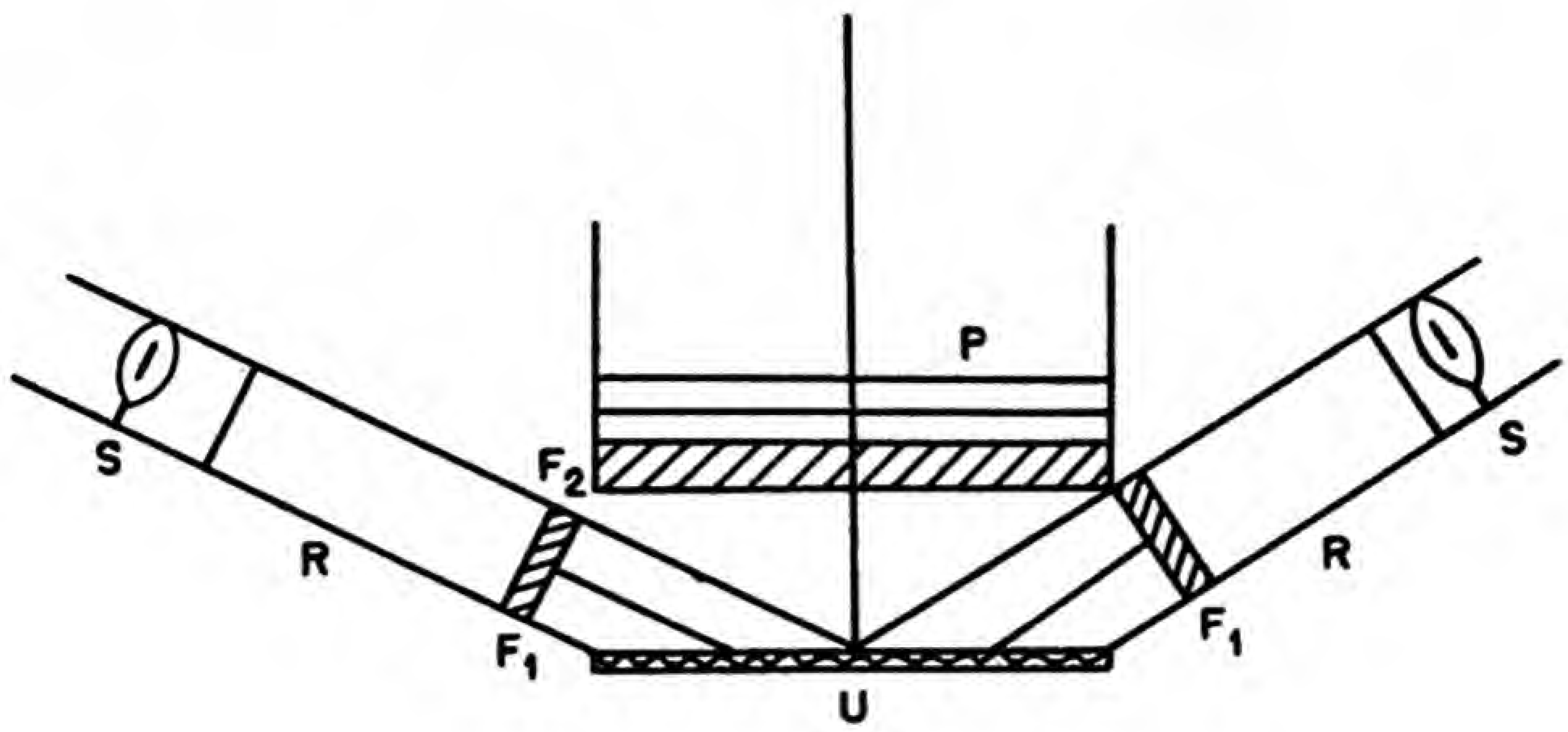


Fig. 3.4—Plastic-rods system.

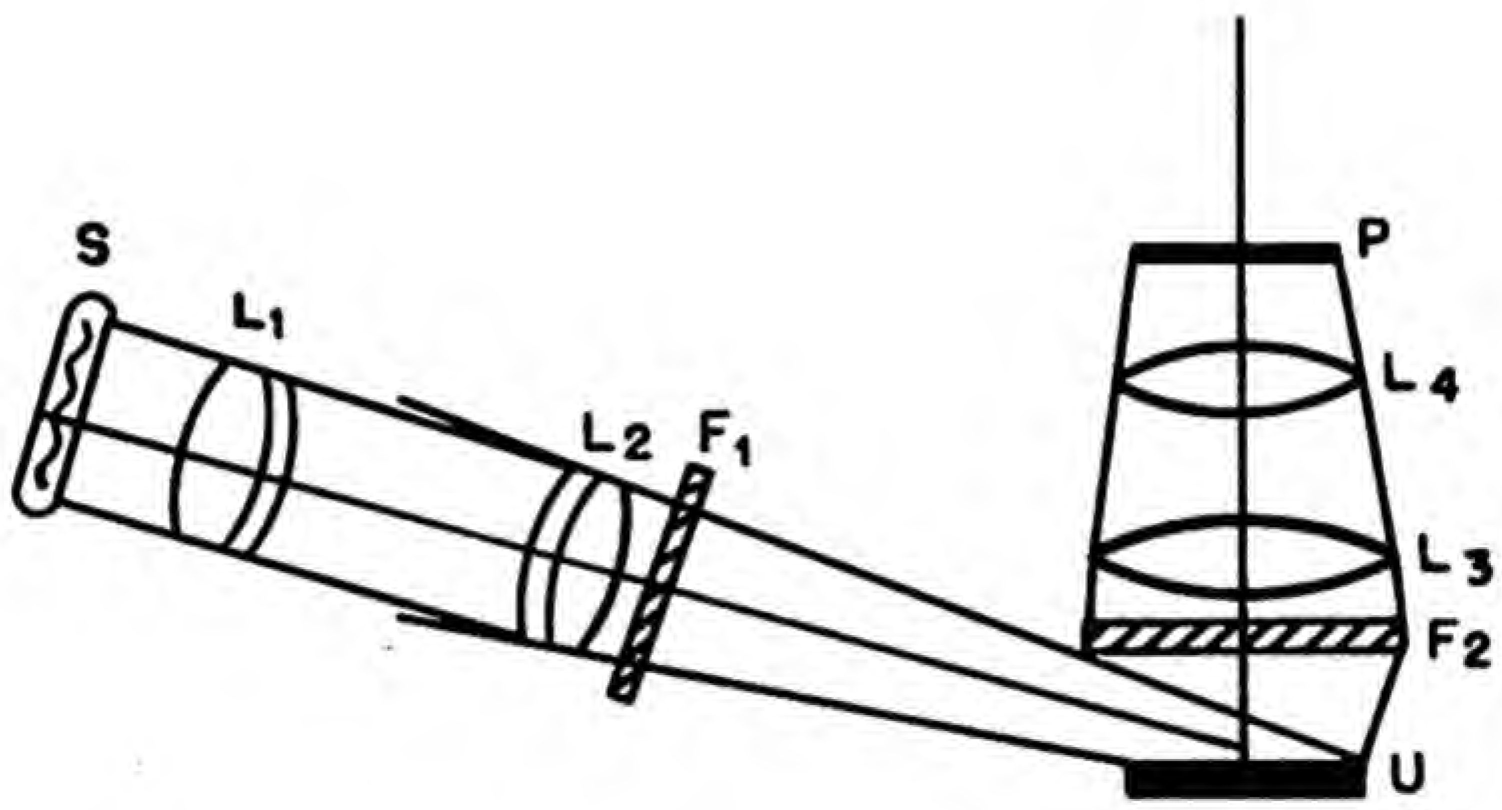


Fig. 3.5—Incident light at a large glancing angle.

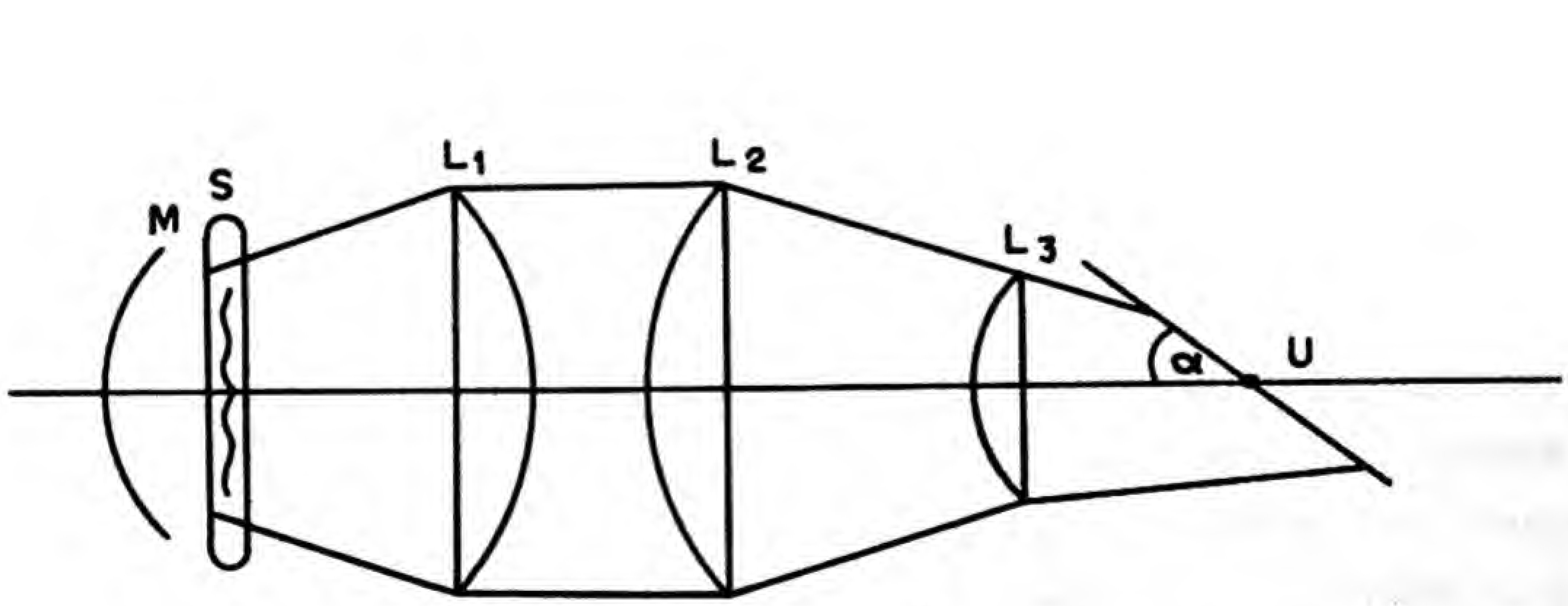


Fig. 3.6—Exciting-light system. MS, 2⁹⁄₃₂ in.; SL_1, 16.7 cm; L_1L_2, 4.5 cm; L_2L_3, 17.4 cm; L_3U, 10.9 cm (to point of U on special axis); α, 25 deg.

Lens	Thickness, cm	Diameter, cm	F.L., cm	Type
L_1	2.0	11.3	18.9	Plano-convex
L_2	1.8	7.7	8.7	Plano-convex
L_3	1.5	3.0 5.6	3.1	Equiconvex, cylindrical

The lenses and the lights for the preceding system are on hand. Corning filter No. 5860 should be placed between L_3 and U in the exciting-light system, and Corning filter No. 3389 should be placed between U and L_1 in the fluorescent-light system.

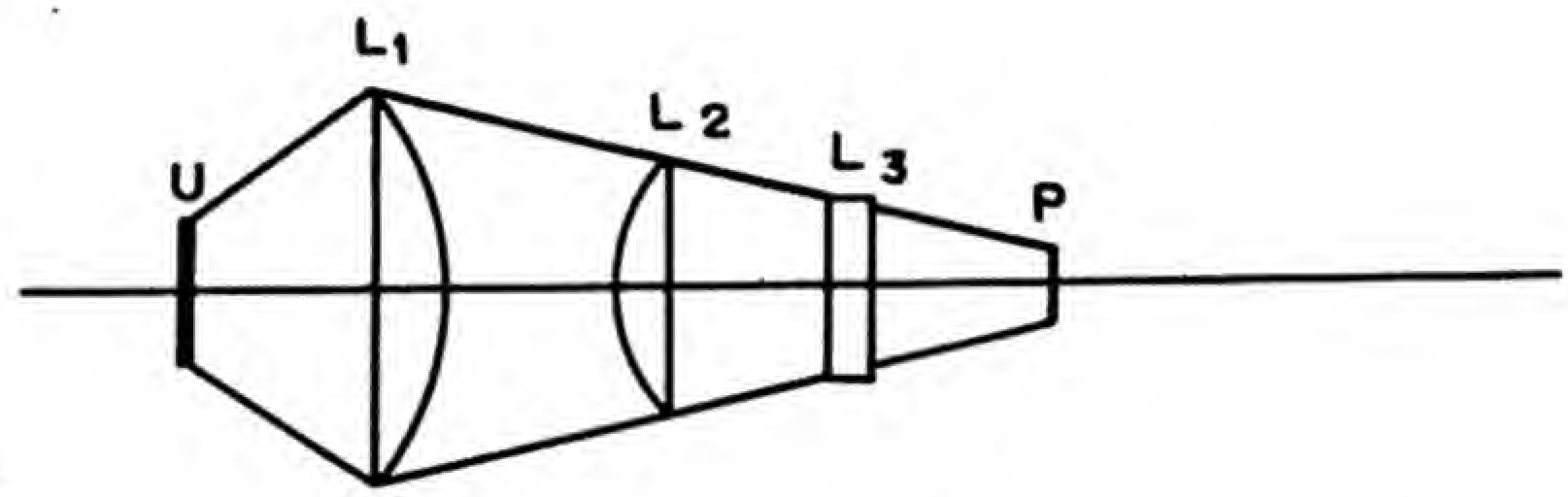


Fig. 3.7—Fluorescent-light system. UL_1, 15.5 cm; L_1L_2, 5.5 cm; L_2L_3, 5.0 cm; L_3P, 1.0 cm.

2. SMOKE TESTER

In order to trace oil smoke from a stack[7] and to discover where the flue gases were going, a smoke tester capable of determining the size and number of smoke particles of the order of 0.04 cm in diameter was developed by the Optics Section.[8]

3. EVAPORATION AND SPUTTERING

The applications of evaporation and sputtering in vacuum are so many and diversified in modern technology that the general method will be described briefly here, and only the developments and applications to Project needs will be discussed in detail. Improved techniques will be indicated.

Sputtering* and evaporation† are used interchangeably in some cases. Thus, for example, a coating of gold may be made with equal

* Also called "cathodic sputtering" and "cathodic pulverization."

† Often called "condensation" and, less often, "distillation" or "vaporization."

ease by either method. The two are treated here in one unit for the further reason that in other instances, for example, platinum, evaporation is so much more difficult than sputtering that the latter is resorted to for expediency if not for economy. Also, as with tungsten, evaporation is slow, but sputtering, being a matter of days, is chosen as the lesser of two evils.

3.1 General Considerations. The two methods of producing coatings of suitable materials in vacuo are basically different. Evaporation consists essentially in boiling or subliming a material, with subsequent condensation of vapor on a "cold" surface,[9–11] whereas sputtering is a process of knocking minute particles out of the surface of a material by bombarding it with ions,[11–18] which particles then cling to available nearby surfaces.

(a) Evaporation. Evaporation must take place in vacuo for two reasons. The first is concerned with the mean free path of the evaporating particles, which at atmospheric pressure is negligible. As the pressure is reduced, the mean free path increases according to the equation[19]

$$\lambda = \frac{1}{\sqrt{2}\pi\eta\sigma^2}$$

where λ is the mean free path in centimeters, η is the number of molecules per cubic centimeter, and σ is the molecular diameter in centimeters. At 10^{-4} mm Hg the mean free path has reached a value of 20 to 25 in.,* which is more than the diameter or height of an ordinary-size bell jar. The particles will now, on the average, travel in straight lines in all directions from the source, until they strike some surface, and they will be able to reach all parts of the vacuum chamber. They will condense on any surface that is relatively cool. The majority of the particles travel a straight-line path, but, especially with the lowest-melting metals, there is a certain amount of diffusion always present, as evidenced by light deposition on the side of a cold surface away from the source.

Because of the character of the particles, they reproduce exactly the surface on which they deposit and do not "fill in" the scratches or pits. A coherent metallic film does not deposit on most waxes, greases, and oils.

The second reason for operating in a high vacuum is to prevent oxidation of the evaporating particles and of the bulk material. When

* This calculation is for nitrogen and is permissible since all molecular diameters are similar in magnitude.

they are heated until the material boils or sublimes, the particles are given sufficient energy to leave the source, and at such a high temperature a reaction with surrounding gases will take place quite readily.

(b) Sputtering. Sputtering, on the other hand, is an entirely different type of process. If a potential is applied between two electrodes in a vacuum of 10^{-1} mm Hg, for example, a glow discharge will occur between them. The characteristics of such a discharge are well described elsewhere;[14,20] therefore it will suffice to say that the present interest is only in the dark space and discharge area near the cathode.

The most acceptable explanation of the phenomenon is that electrons from the cathode bombard gas molecules, creating positive ions which strike the cathode, and through some mechanism knock out or release neutral particles of the substance of the cathode.[14,15] These particles will deposit on any surface placed near the edge of, or just within, the Crookes dark space. This, then, is a means of depositing a film of the cathode metal.

Speed of deposition in sputtering is dependent primarily on the cathode material and the nature of the residual gas. Noble metals are generally first on the list, with others arranged variously by different experimenters.[14] Current density on the cathode surface also directly affects sputtering speed, as might be expected from the mechanism of the process.

3.2 Apparatus. (a) Vacuum System. The most convenient form of vacuum system for evaporation and sputtering consists of a steel base plate with holes for evacuation, electrode leads mounted on a table, a bell jar which is set onto the base plate, and a diffusion pump and fore pump attached beneath. Other forms in which only a top plate lifts off a can-shaped chamber[22] do not provide as much accessibility to electrodes or ease of maintenance.

The base plate should be machined flat and preferably be made of about 1-in. rolled steel or brass. Cast metals are likely to be porous. The diffusion pump is most easily sealed on with a hard wax such as Apiezon W, Plicene, or De Khotinsky, and the electrodes are sealed through the base plate through insulators with Glyptal or a hard wax. A typical assembly is shown in Fig. 3.8. Connection of the mechanical fore pump to the diffusion pump is best made by heavy-walled rubber tubing because of vibration.

For accurate measurement of vacuum, the ionization gauge is most useful. An extra opening in the base plate provides a means of connecting the gauge to the vacuum chamber, and here again hard waxes make the most convenient seal to the side tube of the ionization manometer tube. A suitable external circuit must, of course, be pro-

vided. Calibration of the tube against a McLeod gauge is usually necessary.

Bell jars of glass and of metal are both used, the metal being most helpful when large amounts of heat are generated by heaters, since glass bell jars might not be safe. However, a cylinder of thin sheet metal just within the walls of a glass bell jar is good protection from

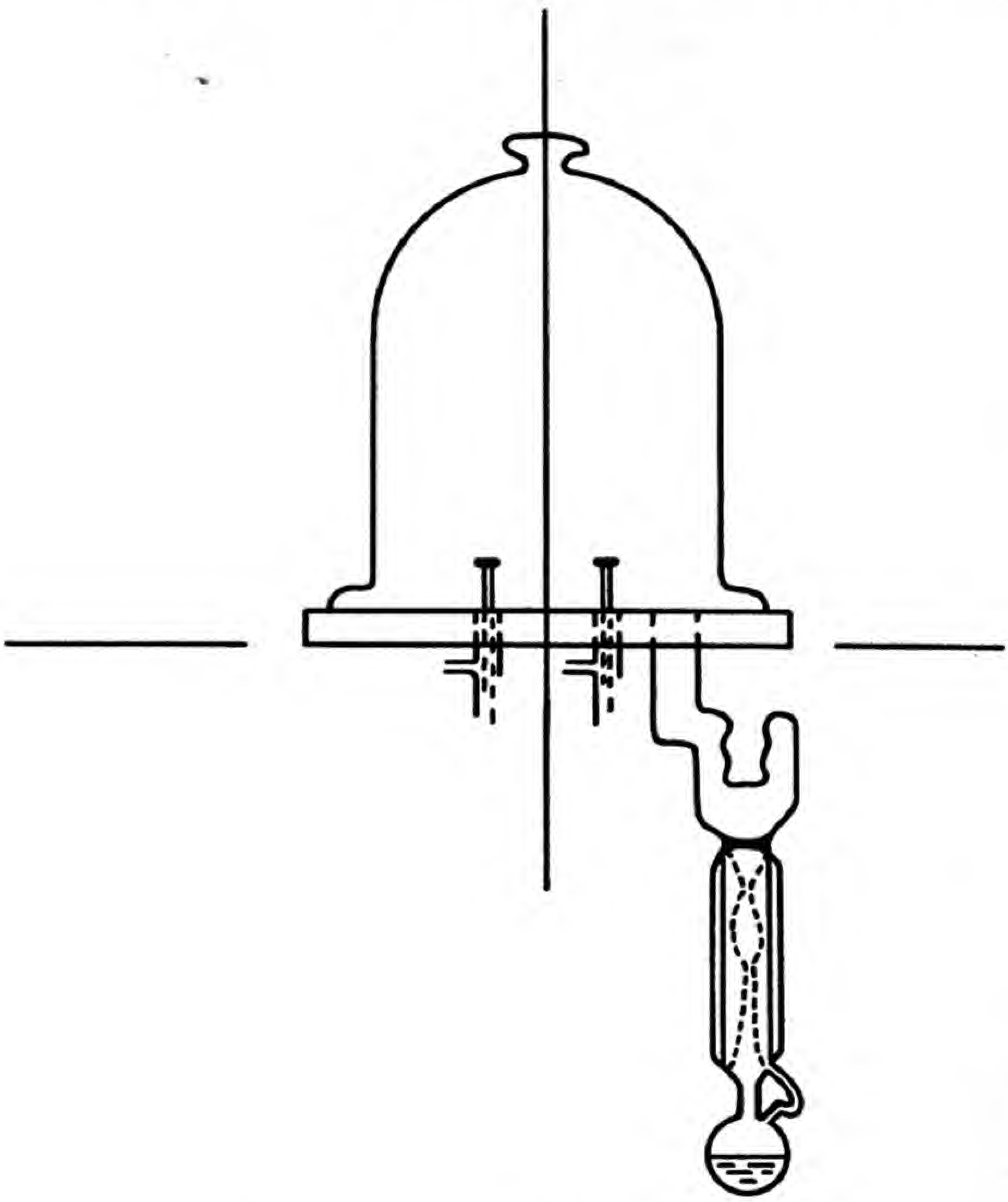


Fig. 3.8—Typical vacuum system for evaporation and sputtering.

radiated heat. Since soldered or welded joints may easily have pinholes, a coating of wax or Glyptal is usually necessary. By drilling a hole through the top of a glass bell jar and sealing in an electrode with radiating fins, a suitable jar for sputtering is provided. The fins dissipate heat generated by the sputtering process sufficiently well to eliminate danger of overheating.

(b) Heater Systems. From each electrode sealed through the base plate, a connecting cable leads to a switch at the control panel. Here electrical connections to one of the power supplies are made.

For resistance heating of filaments and boats, smoothest control is provided by Variac-controlled* step-down transformers. As a typical example, a tungsten "stocking" will draw about 2.5 amp at 60 to 70 volts for the evaporation of silver or gold. Several transformers in series, parallel, or some other arrangement will be found to supply sufficient power for most needs.

(1) Filaments. Heaters classed as filaments are the types made of wire. Diameters of individual wires may vary from 0.002 in. to as much as 0.060 in. The metals most commonly used are tungsten, tantalum, molybdenum, and columbium, in decreasing order of importance. Some of the most common forms are shown in Fig. 3.9. The helical and conical types are easily wound on mandrels threaded to the proper pitch; the U-shaped type is bent by hand or on a flat form; and the stocking, or sleeve, filament† is woven from fine wires in a commercial machine.

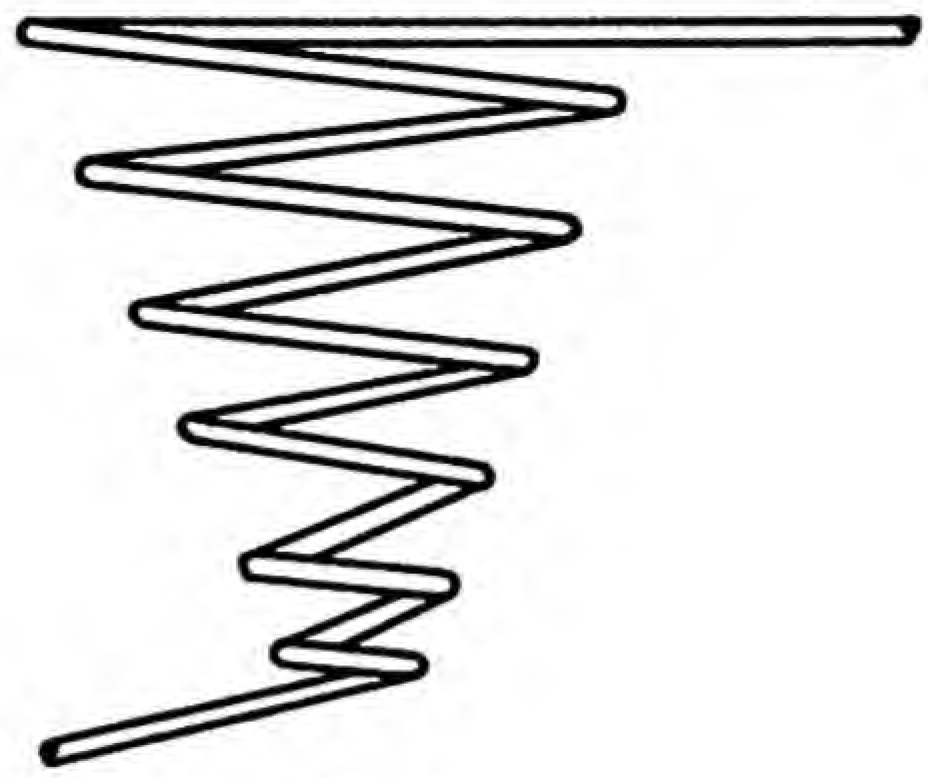
In use, the material to be evaporated is hung or supported on the helical and U-shaped filaments and is placed within the conical and sleeve types.

(2) Boats. All heaters made of strip metal with an indentation of one kind or another are classed as "boats." The materials used are tungsten, tantalum, molybdenum, and columbium, in thicknesses varying from 0.005 to 0.015 in. The indented form (Fig. 3.10) is best made in a die, the V-shaped form by hand shaping in a single piece of strip metal, and the rectangular form by cutting a larger rectangle and bending the parts over one another. Over-all size and thickness of material are determined by what is being evaporated and the size of the receiving surface.

(3) Crucibles. Two shapes of crucibles, conical and cylindrical, are the types commonly used, with minor variations such as rounding of the conical tip or the addition of a closely fitting cover with a small hole. They may be made from oxides, nitrides, carbides, or graphite. The oxides of thorium, beryllium, magnesium, zirconium, aluminum, and yttrium; the carbides of boron, tungsten, and titanium; and the nitrides of boron and titanium are extremely refractory. The casting and forming of crucibles is of wide scope and will not be discussed here.

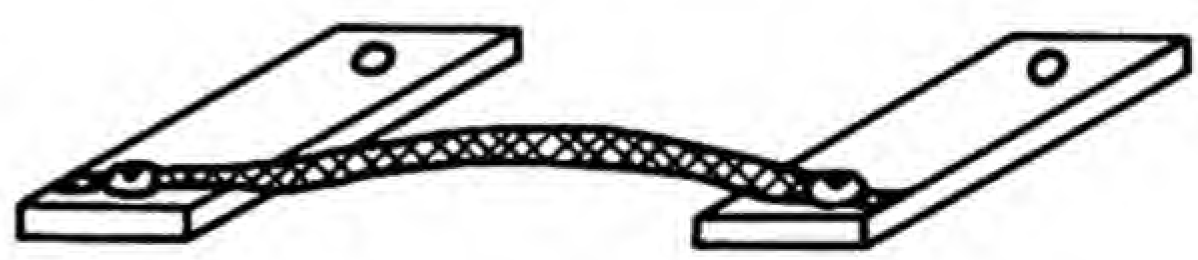
Heating of a crucible is usually accomplished with a tungsten coil closely fitted around the outside, as shown in Fig. 3.11. The outer crucible or sleeve shown is often added merely for greater efficiency in heating, and it is of some refractory material such as alundum or

*The Variac was supplied by General Radio Co., Cambridge, Mass.
† Manufactured by the General Electric Company, Schenectady, N. Y.



(a)

(b)



(c)

Fig. 3.9—Three of the most common filament heaters. (a) Helical. (b) Conical. (c) Stocking.

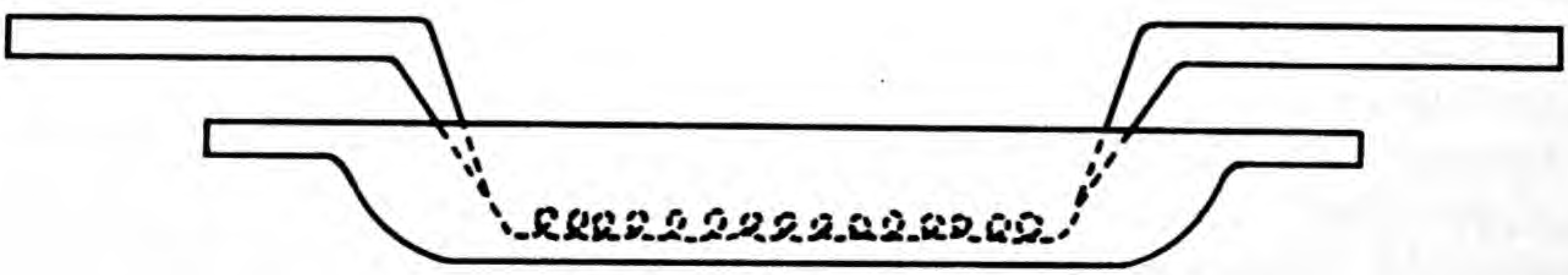


Fig. 3.10—Indented boat.

porcelain. In occasional cases, a sleeve may be of tantalum. Crucibles on the whole are not too satisfactory because they may decompose or react with the evaporating material at high temperatures. More often than not, some volatile impurity causes a powdery or chalky coat to appear on the object of evaporation. Highest quality work can best be done from bare metal heaters.

(4) Combinations. Most heater combinations have the purpose of concentration of heat in a small space. Arrangements such as a helical filament within a stocking filament, a refractory boat within a

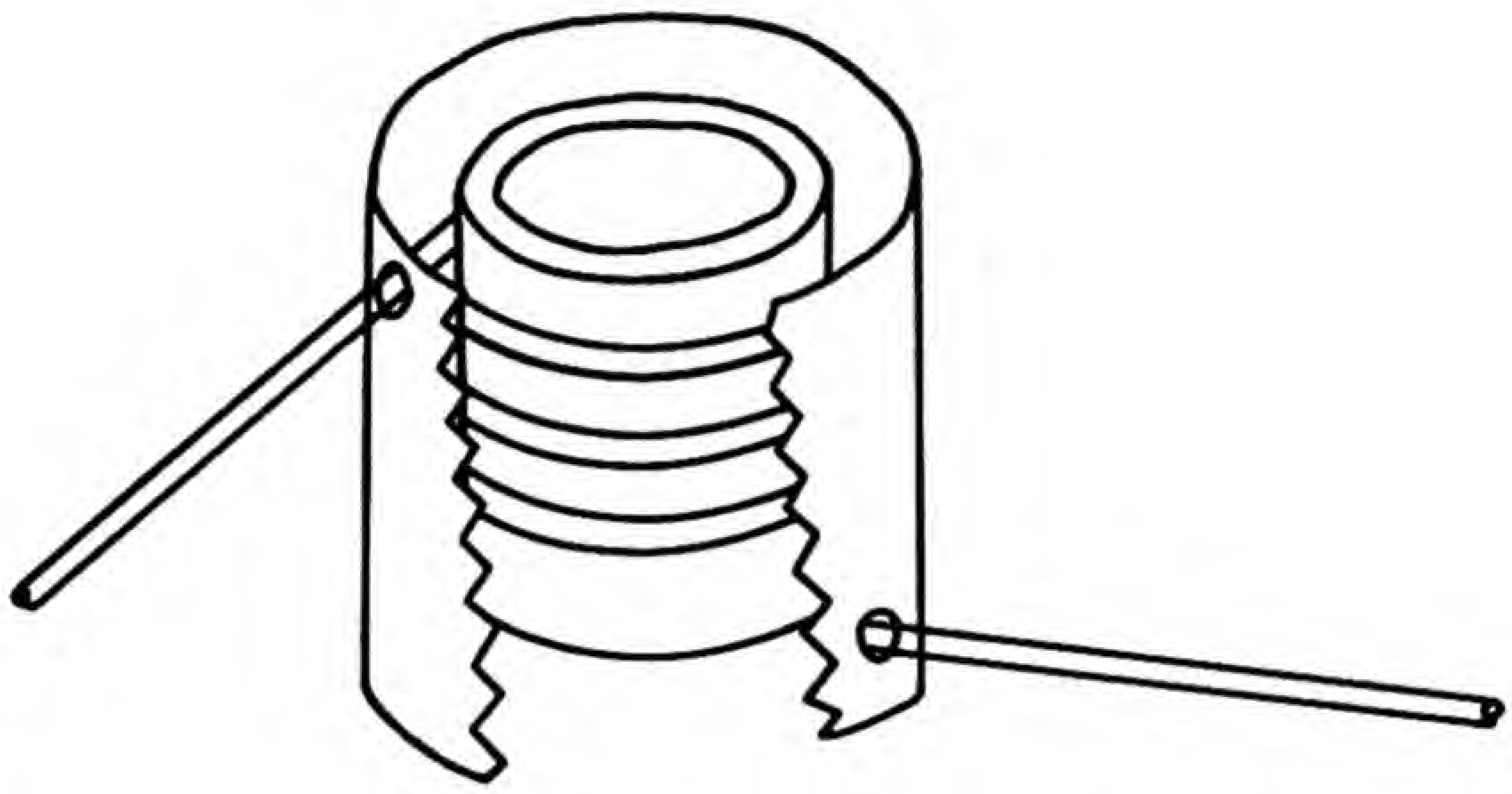


Fig. 3.11—Crucible with tungsten coil and outer sleeve.

helical filament, a helical filament within a perforated refractory tube (this can be extruded of thoria), a U-shaped tungsten filament dipping into a refractory boat filled with material to be evaporated, or a cylindrical graphite crucible with helical filament passing down the center have all been used to attain higher temperatures than would be possible with a single element of the combination. These are but a few and will suggest many others.

(5) Miscellaneous Types. In addition to these there are many other types of heaters.

(6) Carbon Heaters. Carbon heaters have been used in several ways. When a tube of carbon filled with material to be evaporated is heated, the material will in certain cases pass through the walls of the tube and deposit as usual. Tubes or rods of carbon may be painted with a powdered material and heated to produce evaporation, or a perforated carbon tube filled with material can be resistance-heated for the same purpose. Since carbon is easily machined, such heaters are often comparatively easy to make.

One other method of heating which has not been very successful but which is worth mention is that of producing an arc between electrodes immersed in the material to be evaporated.

These types, included as "combinations" and "miscellanea," are used only occasionally and then only for very-high-melting materials or those difficult to evaporate. Filaments are most widely used and may be painted, if desired, with a thin layer of refractory such as thoria or magnesia in order that, especially in the conical form, no possibility of shorting out of single turns will occur.

(7) Induction Heaters. A method of evaporation which is finding increased utility is high-frequency induction heating. One of its advantages is that the heater may be supported within the vacuum chamber without electrical connections, and the induction coil may be left outside the walls of the chamber. Again, the heater, which is often a graphite or tantalum crucible, may be raised to a high temperature within a very short time. This speed in heating is useful, as is the fact that temperatures higher even than the melting points of ordinary crucible materials can be attained. Greater application of induction heating to the evaporation technique will occur in the future.

(8) Electron Bombardment. By utilizing the electrons emitted by a hot filament for further heating of the material to be evaporated, a high concentration of heat may be developed. A simple schematic diagram of the necessary circuit is shown in Fig. 3.12, where the filament is heated by a Variac-controlled transformer and a high-voltage d-c potential is imposed between a graphite or tantalum crucible and the filament. As much as 2000 to 5000 watts may be concentrated in a small crucible by this means.

3.3 Procedures. (a) Preparation of Materials. In making a film deposition, much care must be taken to ensure the proper purity of materials. Traces of impurity in an evaporated metal can spoil the quality of a film as easily as insufficient cleaning of the receiving surface.

Impurities in the material deposited may affect a coating in several ways: darkening of the surface can be attributed to contamination by grease, oil, or foreign metals, and a whitish film may indicate the presence of oxides or other compounds. When refractories are used, the refractory material or its impurities may deposit a whitish film. It is usually difficult to say just which factor has contributed to poor quality.

However, little difficulty will be encountered in making a good film if a metal is reasonably pure (approximately 97 per cent or better); if it is free of oxide; if it has been cleaned of all grease (even fingerprints) by washing with pure benzene, chloroform, or other solvents; and if it has been perfused or, preferably, prefired in vacuum.

After the surface is thoroughly cleaned with a solvent, it should be swabbed repeatedly with a detergent (or a dilute suspension of precipitated chalk in water where this would not scratch the surface) until the rinsing water does not draw away from any part of the surface but adheres in a continuous film. Copious rinsing must follow to remove all traces of cleaning agent, after which blowing off (not evaporating) the film of water with filtered compressed air will leave a surface exceptionally clean.* Rubber gloves should be worn to avoid fingerprints.

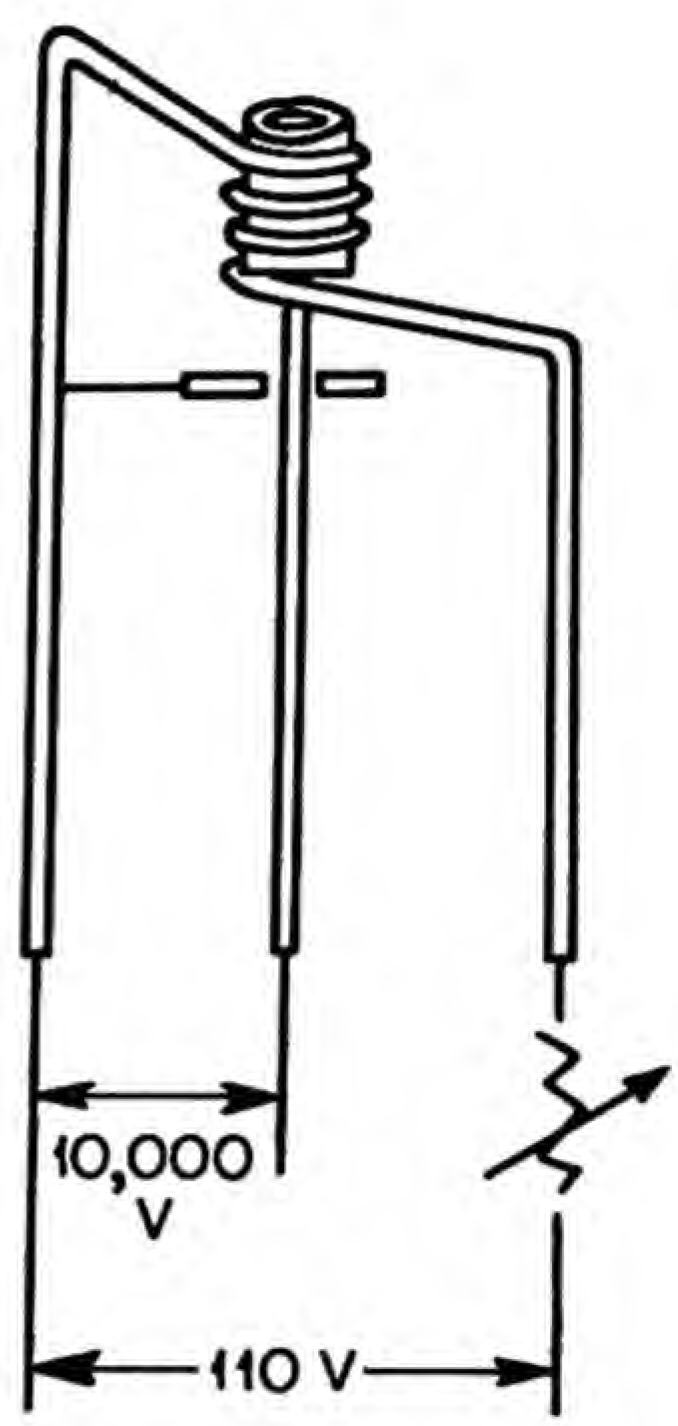


Fig. 3.12—Schematic diagram of circuit for heating by electron bombardment.

If it is desirable to increase the tenacity of deposited film, heating the sample before, and even during, deposition will tend to produce a harder coat. Nichrome heaters are satisfactory for this purpose. Exposing the surface to a glow discharge in the vacuum chamber is another method of further cleaning surfaces to produce a better coating.[11]

(b) Deposition of Films. The first step in the preparation of a film is to determine whether evaporation or sputtering will be most efficient. Generally, for metals boiling below about 1500°C, evaporation from a bare tungsten or tantalum heater is very easy. This same

* For very-high-quality mirrors, certain other precautions are necessary. These are described in Sec. 3, Chap. 2.

technique may be used up to boiling points of about 1800°C, but with more difficulty. Above this, refractories or carbon heaters are usually necessary, or some method such as electron bombardment or induction heating is necessary. Thus sputtering becomes useful where evaporation is impractical, since sputtering requires no heating of the material. For nonmetallic substances, of course, evaporation must be used exclusively. In cases where both evaporation and sputtering are easy, as with gold, other considerations, such as the amount of metal used, are deciding factors. Specific details on various materials are given in Tables 3.1 and 3.2.

In making an evaporation, the proper type of heater or filament is connected by fittings or extensions to a pair of electrodes within the vacuum system, and all electrical connections are made secure. After the material is placed in the heater and the receiving surface is set so that all parts are as nearly equidistant as possible from it, a bell jar is placed over the assembly and sealed with a greased rubber gasket,* wax, or Apiezon Q. When a vacuum of at least 10^{-4} mm Hg has been reached, heat is applied and the material is evaporated, usually until the glowing heater can no longer be seen through the walls or window of the bell jar. Some metals and nonmetals boil as they evaporate, and a few sublime.

Chemical methods of cleaning off the walls of the bell jar are usually best, although sometimes a coating is soft enough immediately after breaking the vacuum to be wiped off with a cloth.

In the sputtering process, a plate or sheet of the metal to be deposited is suspended from an electrode sealed through a hole in the top of the bell jar.[11] This cathode may be curved if the object of deposition is curved, or it may be a rod if the inside of a tube is to be coated. It may be a cylinder in order to coat all sides of an object, such as a group of quartz fibers or the outside of a cylinder. The object to be coated must be well cleaned, and it should be placed from ½ to 1½ in. from the cathode, depending, respectively, on whether the cathode surface is small or large. The anode of the system may be any surface of metal (the base plate of the vacuum system is suitable) so long as it is not close to the cathode. When the bell jar is sealed in place and a vacuum of about 1 mm Hg is reached, a potential of from 1000 to 10,000 volts applied to the cathode and anode of the system produces the characteristic glow discharge in which sputtering

* This can be cut from 1/32-in. Neoprene or other oil-resistant rubber compound with an outer diameter nine-tenths that of the bell-jar lip and a width of about 1 to 1¼ in. After greasing with stopcock grease, it is stretched over the edge of the bell-jar lip, to which it conforms perfectly.

takes place. Either alternating or direct current may be used, although direct current is more satisfactory from the point of view of ease of operation and purity of the resulting film.

When the potential is first applied, difficulty is ordinarily encountered in that outgassing and surface impurities will cause sudden surges of current which seriously overheat electrodes. These surges are accompanied by bright flashes of excessive ionization and may be subdued by inserting a suitable series resistor in the circuit. Usually after about ½ hr of operation, the system will have settled down and the current density of the cathode should then be adjusted to an optimum (limited by overheating of the sealed-in cathode lead). The length of time for deposition of an opaque coat then varies with the metal being deposited, the nature of the residual gas, and the cathode current density.

3.4 Application of the Method. Differences in technique for different materials are demanded by varying physical properties. In some cases sputtering is advisable, whereas in the majority of cases evaporation is most efficient.

In Table 3.1, atomic number, melting point, and boiling point are included for reference purposes. Boiling points at 10^{-2} mm Hg are taken from Strong[11] (p. 169). All others are given for atmospheric pressure. Heaters referred to are of the types described in Sec. 3.2b, and methods of deposition are mentioned in order of preferred choice where more than one is indicated.

3.5 Low-reflection Coatings. Since the technique of evaporation was first applied[36] to low-reflection coatings in 1936, several more recent methods have been developed for that purpose. All have the common function of producing a very thin film of a nonmetallic substance on the surface of a lens, prism, or window.

The mechanism of reducing reflection consists in destructive interference of the ray reflected from the air-film interface by those multiply reflected from the film-glass interface. Thus in Fig. 3.13 the reflected rays 2, 3, 4, . . . are in phase with each other because of path differences and phase changes at reflection but are 180 deg out of phase with the primary reflected ray 1. They effectively cancel it as a result. The derivations of the equations for the thickness and refractive index of such films have been made very simply from the Fresnel formulas,[37,38] to a second degree of approximation[39] and exactly.[40] These equations show that in order to effect the complete extinction of the reflection ray, the thickness of the film must be one-fourth the wavelength that the light has in the film, and its refractive index must be the square root of that of the base material. In practice, this is impossible to achieve simply because materials

Table 3.1—Deposition of Single-element Metallic Films

Element	Atomic No.	Melting point, °C	Boiling point, °C: Atmospheric pressure	Boiling point, °C: 10^{-2} mm Hg	Methods of deposition	Remarks
Silver (Ag)	47	960.5	1955	1319	W stocking; W, Ta, or Mo boat; Mo or Ta helical or conical filament[23]	Does not wet W or graphite; wets Ta and Mo slightly; sputters easily
Aluminum (Al)	13	658.7	1800	1461	W filament, U-shaped or helical[11]	Wets W and Mo thoroughly and alloys with W; do not use boats or crucibles for evaporation; very low sputtering rate, except under certain conditions[24]
Gold (Au)	79	1063	2600	1445	W, Ta, or Mo stocking; W, Ta, or Mo boat	Wets W, Ta, and Mo; evaporation is slow to start, then occurs suddenly; coats are quite soft; sputters easily
Boron (B)	5	2000–2500	Sublimes at 2250		Heating a graphite rod coated with boron;[25] electron bombardment of a graphite crucible[26]	Very difficult to evaporate; sputters very slowly

Beryllium (Be)	4	1350	1530		W or Ta stocking; conical W or Mo filament; coating of filament with thoria is helpful[27]	Wets Mo and W; is somewhat difficult to evaporate
Bismuth (Bi)	83	271.3	1436	913	W, Ta, or Mo boat or stocking; conical filament may be used if closely wound, otherwise Bi will drip out	Very easy to evaporate; wets W, Ta, and Mo to some extent; sputters easily[24,28]
Carbon (C)	6	Sublimes above 3500	4200	2795	Electron bombardment of carbon[26]	Very difficult to evaporate; sputters extremely slowly[24]
Columbium (Cb)	41	1950	>3300		Resistance heating of a Cb wire	Evaporates very slowly
Cadmium (Cd)	48	320.9	778	541		Sputters easily in an H_2 atmosphere[24]
Cerium (Ce)	58	640	1400		Ta boat	Wets Ta; evaporates rather easily
Cobalt (Co)	27	1480	2000			Evaporates fairly easily;[26] sputters fairly easily[28]
Chromium (Cr)	24	1615	2200	119	Any stocking, conical, or helical filament	Evaporates rather slowly; sputters very slowly[24]
Copper (Cu)	29	1083	2310	1542	Any Ta or Mo filament	Wets Ta or Mo, but not W;[11] sputters fairly easily[28]

Table 3.1—(Continued)

Element	Atomic No.	Melting point, °C	Boiling point, °C: Atmospheric pressure	Boiling point, °C: 10^{-2} mm Hg	Methods of deposition	Remarks
Iron (Fe)	26	1535	3000	1694		Wets W;[11] sputters fairly easily[28]
Indium (In)	49	156.4	>1450		Ta or Mo boat	Wets Ta or Mo
Iridium (Ir)	77	2454	4400			Can be plated onto W filament and evaporated off[11]
Magnesium (Mg)	12	651	1110		W filament	Sublimes when evaporated[11]
Manganese (Mn)	25	1260	1900		Conical W filament, or graphite crucible[27]	Evaporates easier than chromium, giving a very hard, usually somewhat dark coat
Molybdenum (Mo)	42	2535	3620	2755	Resistance heating of a Mo wire; electron bombardment of a graphite crucible containing molybdenum[28]	Several days are required to produce an opaque coat by first method[29]
Nickel (Ni)	28	1452	2900	1717	Sputtering is most satisfactory	Difficult to evaporate; sputters very easily
Osmium (Os)	76	2700	4450			Can be plated onto W filament and evaporated off[11]

Lead (Pb)	82	327.5	1525	1000	W, Ta, or Mo stocking or boat	Does not wet W, Ta, or Mo; sputters very easily;[24] tarnishes quickly on exposure to air; evaporates very easily
Palladium (Pd)	46	1555	2200			Can be plated on W filament and evaporated off;[11] sputters readily, but is usually dark in color[24]
Polonium (Po)	84	1800				A flattened portion of a Ni, Pd, or Pt wire serves as an evaporating source[30,31]
Platinum (Pt)	78	1755	3910	2332	Sputtering is most satisfactory; can be evaporated from a graphite crucible[28] or a plated W filament	Sputters very readily; alloys to such a great extent with W heaters that they usually burn out
Rhenium (Re)	75	3167				Can be plated onto W filament and evaporated off[11]
Rhodium (Rh)	45	1985 ± 15	>2500			Can be plated onto W filament and evaporated off;[11] makes very bright durable tarnish-resistant mirrors

Table 3.1—(Continued)

Element	Atomic No.	Melting point, °C	Boiling point, °C: Atmospheric pressure	Boiling point, °C: 10^{-2} mm Hg	Methods of deposition	Remarks
Ruthenium (Ru)	44	2450	4150			Can be plated onto W filament and evaporated off
Sulfur (S)	16	112.8 119.3	444.7		Conical W filament	Appears as small transparent globules which becomes opaque after several hours[32]
Antimony (Sb)	51	630.5	1635 ± 8	973	Ta, Mo, or W boat; stocking or closely wound filament; sputtering	Evaporates all at once in a dense cloud and often peels off condensing surface as it deposits, usually before an opaque coat is attained; does not wet Ta; sputters very easily[28]
Selenium (Se)	34	217	688		W, Ta, or Mo boat; closely wound filament[32]	Does not wet Ta; may condense in the red crystalline form rather than the gray stable crystalline form
Silicon (Si)	14	1420	2600		Electron-bombarded graphite crucible;[26] filament-heated thoria crucible[27]	Alloys with W and Mo and burns out heaters;[27] sputters very slowly[28] even in Hg vapor[24]

Tin (Sn)	50	231.9	2270	1148	Conical W filament; boats and stockings not satisfactory	Wets W and Ta; slow heating is desirable; takes much heating to evaporate; sputters readily;[28] oxidizes easily after deposition
Tantalum (Ta)	73	2850	>4100		Resistance heating of Ta wire	Very slow to evaporate
Tellurium (Te)	52	452	1390			Sputters somewhat easily[28]
Thorium (Th)	90	1845	>3000		Conical W filament; sputtering	Wets W; sputters fairly easily;[34] evaporates easily
Uranium (U)	92	1100 ± 25 (ref. 26)	~4300 (ref. 26)		Conical W filament, with U in good thermal contact	Wets W; evaporates slowly under vacuum at about 2100 to 2200°C; sputters fairly easily[34]
Vanadium (V)	23	1715	3400		Electron bombardment of a graphite crucible[26]	
Tungsten (W)	74	3370	4727	3505	Resistance heating of a W wire	Takes several days to obtain opaque coat by evaporation;[29] slow in sputtering[28]
Zinc (Zn)	30	419.4	907	623	Any boat or stocking; beryllia crucible	Does not wet Ta or Mo; sublimes in evaporation; diffuses into beryllia crucible; easy to sputter[28]
Zirconium (Zr)	40	1700	>2900		Electron bombardment of a graphite crucible[26]	

Table 3.2—Deposition of Alloyed or Compounded Metallic Films

Alloy or compound	Methods of deposition	Remarks
Advance	W coil	Adheres well to coil
Ag-Pt	Resistance heating of a Pt-Ag alloy wire	Silver evaporates, leaving Pt behind[10]
Al-Cr	W filament of any type	Wets W; produces hard brilliant wear-resistant mirror surfaces; see Sec. 3, Chap. 2
Al-Cu	W filament	Gives darker film than pure Al
Al-Mg	W filament	Wets W; good mirror-surface films
Al-Mg-Co	W filament	Films are dark and soft
Al-Mg-Mn	W filament	Slightly dark but tenacious film; wets W
Al-Mn	W filament	Slightly dark film
Al-Pt	W filament	Very good hard durable mirror-surface films
Al-Sb	W filament	Good mirror-surface film[29]
Bi-Sb	Any boat or stocking; Pt is not satisfactory	Alloys with Pt and burns heaters through; film darkens in a day or two on exposure to air; used in thermocouples
Bi-Sn	Same as Bi-Sb	Same as Bi-Sb
Brass	Resistance heating of brass wires to deposit Zn	Zn evaporates out from this Cu-Zn alloy, leaving the Cu behind[10]
Calcite ($CaCO_3$)	Tungsten conical filament[32]	
Co-Al-Mg		See Al-Mg-Co
Cr-Al		See Al-Cr
Cu-Al		See Al-Cu
Cu-Sn-P		See phosphor bronze
Cu-Zn		See brass
Cu-Zn-Ni		See German silver
German silver	W filament	Wets W; evaporates easily
Lucite	Pt crucible heated by W coil	Films are transparent if very thin, opaque if thicker; very soft unless subsequently baked, whereupon they become harder
Magnalium (Al-Mg)		See Al-Mg
Mg-Al		See Al-Mg
Mg-Al-Co		See Al-Mg-Co
Mg-Al-Mn		See Al-Mg-Mn
$Mg-F_2$	Zr boat or closely wound coil; W, Ta, or Mo boat or stocking or closely wound coil; unless already fused, should be moistened to hold the mass together	Used in low-reflection coatings on lenses and prisms; must be especially purified for such use; burns through Pt heaters very quickly; W, Ta, and Mo heaters slowly; and through Zr heaters very little

Table 3.2—(Continued)

Alloy or compound	Methods of deposition	Remarks
Mn-Al		See Al-Mn
Mn-Al-Mg		See Al-Mg-Mn
NaCl	W conical filament[32]	
Ni-Cu-Zn		See German silver
P-Cu-Sn		See phosphor bronze
Phosphor bronze	Resistance heating of a phosphor bronze wire to evaporate out Sn	Sn evaporates out, leaving Cu behind[10]
Polystyrene	Same as Lucite	Same as Lucite
Pt-Ag		See Ag-Pt
Pt-Al		See Al-Pt
Quartz	W conical filament	Difficult to evaporate[32]
Sb-Al		See Al-Sb
Sb-Bi		See Bi-Sb
SiO_2		See quartz
Sphalerite (ZnS)	W conical filament	A vacuum better than 5×10^{-4} mm Hg is necessary[35]
Sn-Bi		See Bi-Sn
Sn-Cu-D		See phosphor bronze
$TlCl_2$	W conical filament[32]	
Zn-Cu		See brass
ZnS		See sphalerite

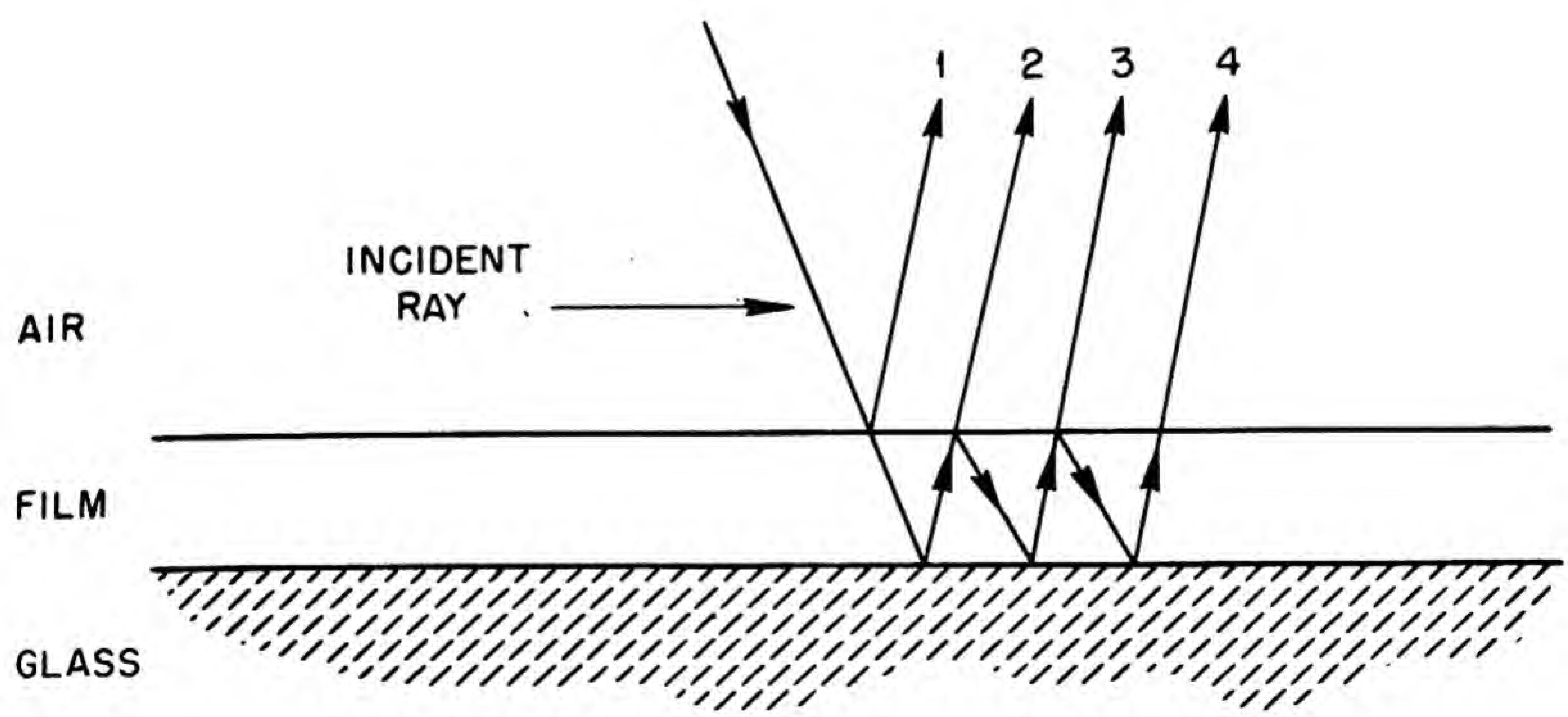


Fig. 3.13—Reducing reflection.

of a low enough index of refraction are not suitable for such films. The thickness may be adjusted to one-fourth the wavelength by stopping deposition when the color of the film has reached a specified hue. For monochromatic light, a low-reflecting film shows no color, but in white light it functions most efficiently for those wavelengths for which it has the approximate thickness of $\lambda/4$. Other wavelengths appear partially as reflected light and thus cause the color of a film. For white light, reflection of the green component is usually reduced to a minimum, since this is the region of greatest visual sensitivity. The residual reflected light from such a film appears purple.

It is interesting that when reflection is completely annulled the transmitted light is 100 per cent of the incident light, neglecting slight absorption, as could be expected from the law of conservation of energy. Thus losses of light in an optical system such as a periscope or well-corrected camera lens, which may amount to as much as 80 per cent,[41–43] can be reduced by a large fraction. A reduction to 10 per cent loss is not unusual. The increase in light transmitted, however, is not the only beneficial result; a reduction in intensity of false images or "ghosts" and an increase in contrast are of especial value in photographic lenses[41,44] and in complex periscopes.[42]

Glass will acquire a natural low-reflecting film if exposed to the elements for long periods of time.[43] The same effect may also be produced chemically;[45,46] it is caused by the formation of a thin skeletal structure of silica which has a lower index of refraction than the glass. This film has the advantages of being as hard as the glass and very durable, and it has the disadvantage of not decreasing reflection as much as evaporated films. Artificial skeletal films have been applied to glass surfaces by building a film of 50 per cent cadmium arachidate and 50 per cent arachidic acid and then leaching out the acid to leave a skeletal structure of the salt which acts just as a silica film.[47]

The low-reflection qualities of the film produced by evaporation of a metallic salt in vacuo can be enhanced by several means. One method is the raising of the pressure during evaporation, resulting in the production of a film increasingly porous toward the surface.[36] The refractive index is decreased below its normal value for a high-vacuum-deposited coat, and the net result is an approach to the theoretically ideal coat having a refractive index equal to that of the glass at the film-glass interface and equal to that of air at the film-air interface.

A nearer approach to the absolute minimum of reflection is made by double or multiple films.[48–51] This first film (or first few) deposited has a higher index of refraction than the glass, and the last

(or last few) has a low index. Thus, effectively, the index of refraction of the glass is raised to a point where the index of the low-reflection film is the square root of that of its substrate. Very close to 100 per cent transmission has been achieved by this method.

The softness of evaporated films is their greatest disadvantage, beyond the great care necessary in making them. They may be hardened somewhat by baking,[49] at the expense of a slight loss in reflection reduction, and they may be waterproofed with a soap or oil film.

The most easily deposited film is that developed by the American Optical Co. as a solution which is spun onto surfaces to be coated. Its chief disadvantage is the streaky or splotchy coat it sometimes produces if conditions of deposition are not carefully controlled. However, the ease and speed with which it is deposited are much in its favor. This and the evaporated film are best from a theoretical point of view.

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Part II

COLLECTED PAPERS

Paper 1.1

A STANDARD PERISCOPE DESIGN FOR PROJECT PURPOSES*

By George S. Monk

ABSTRACT

Consideration is given to optical requirements in several Project areas, and the general optical systems of periscopes are discussed. Illustrative diagrams of several variations of periscopic design are also included.

1. GENERAL DISCUSSION OF REQUIREMENTS

In considering the optical requirements in Project areas, it is not always easy to foresee the particular sort of instrument most appropriate in any location. Certain required features, however, are evident, with emphasis sometimes on one feature and sometimes on another. For instance, the instruments to be used through the 7-ft shield of a pile may be inserted only when the pile is shut down unless the instruments have been "loaded" with shielding material. In other cases, as in the borescope for tubes, the length must be excessive, 33 ft over-all, and the diameter only 1.375 in. Similarly, a smaller borescope ⅛ in. in diameter and up to 18 in. long is desired for the inspection of numerous interiors to detect faults whose exact nature may not be predictable. In the hot-laboratory slug box,[1] a conventional optical system is bent through four right angles.

Instruments must meet the following special requirements:

1. Essentially, the instrument must move the eye to the other side of a radiation shield.

2. The instrument must enable the eye to scan the area at the other side of the shield.

*This paper is based on Report CP-1246.

3. The instrument, by reason of its construction, its shape, or the aperture through which it is introduced, must shield the observer from radiation.

4. The optical parts must be protected from coloration by radiation or must be of materials not so colorable.

1.1 <u>Lens Train of a Periscopic Scanning Sight</u>. The first two of the required features belong to an optical design that contains the lenses and other optical parts of a simple periscope consisting of two telescopes in juxtaposition.

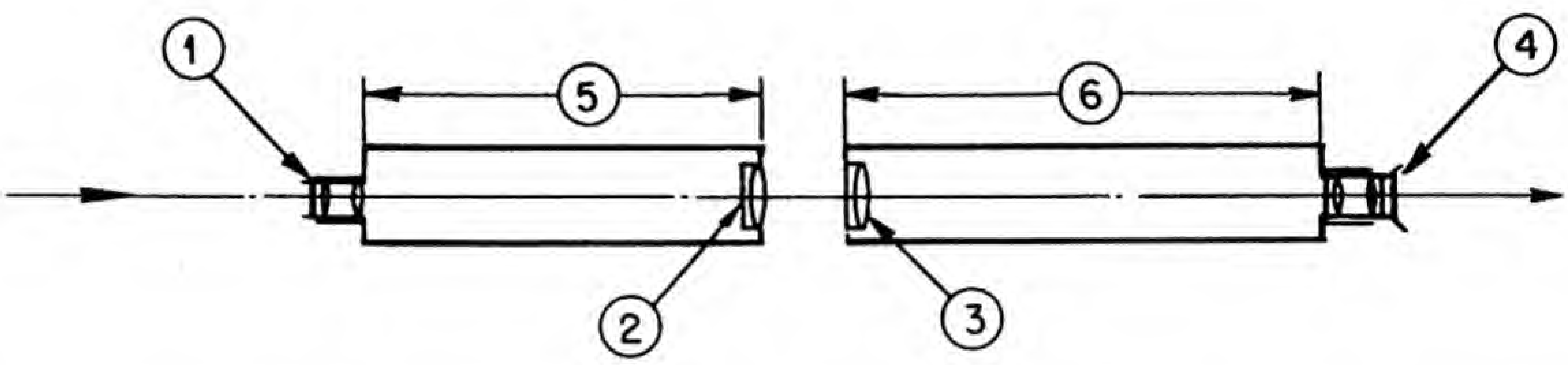


Fig. 1—Lens train of simple scanning sight. (1) Objective. (2) First erector. (3) Second erector. (4) Ocular. (5) First telescope. (6) Second telescope.

The lenses that are involved are shown in Fig. 1. A periscope constructed of these four lenses can be made up so that it may be as short as about 30 in. and may be extended at will. The angle of view observed for a given separation of the two parts depends on the apertures, separations, and construction of the lenses. It is greatest when the two telescopes are placed close together; it decreases slowly at first and quite rapidly for larger distances as the distance between the two telescopes is increased (Fig. 2). In one type of airplane drift sight, an angle of view of 30 deg can be observed when the two telescopes are together.

When a longer instrument is needed, for example, to see through an 8-ft shield, a third element or extender composed of two or more lenses can be placed in the optical path (see Paper 1.2). There are several different types of extenders, among which are the following:

Type 1 (Fig. 3) is simply a pair of achromats of equal focal length a distance apart equal to the sum of the focal lengths. This arrangement increases the field of view and completely inverts the image but does not change the magnification.

Type 2 (Fig. 4) consists of a specially designed system of lenses and is usually designed to fit the optical characteristics of the periscope to which it is adapted. It will not invert the image and is not particularly effective in increasing the field of view.

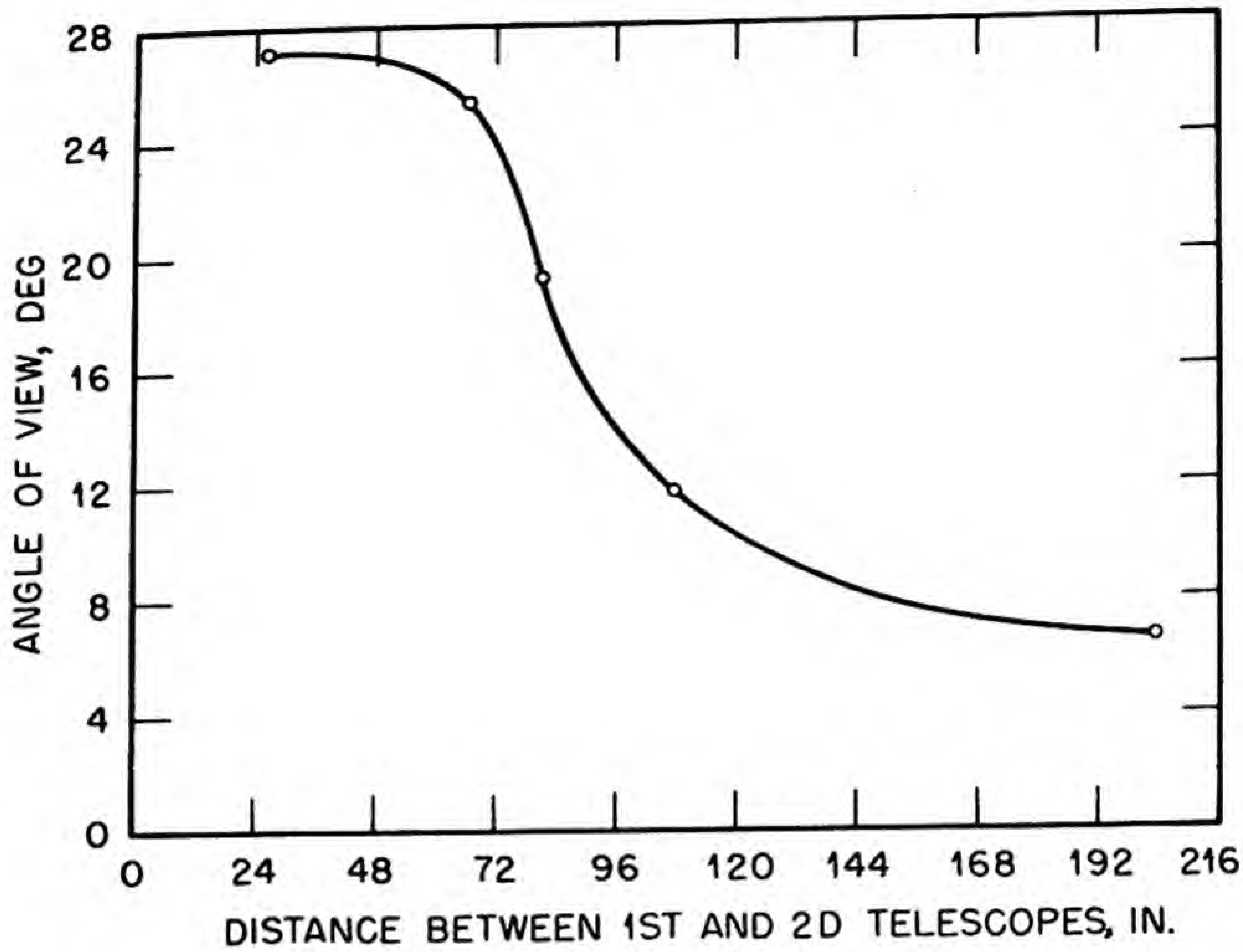


Fig. 2—Dependence of angle of view upon the telescopic separation for a scanning sight.

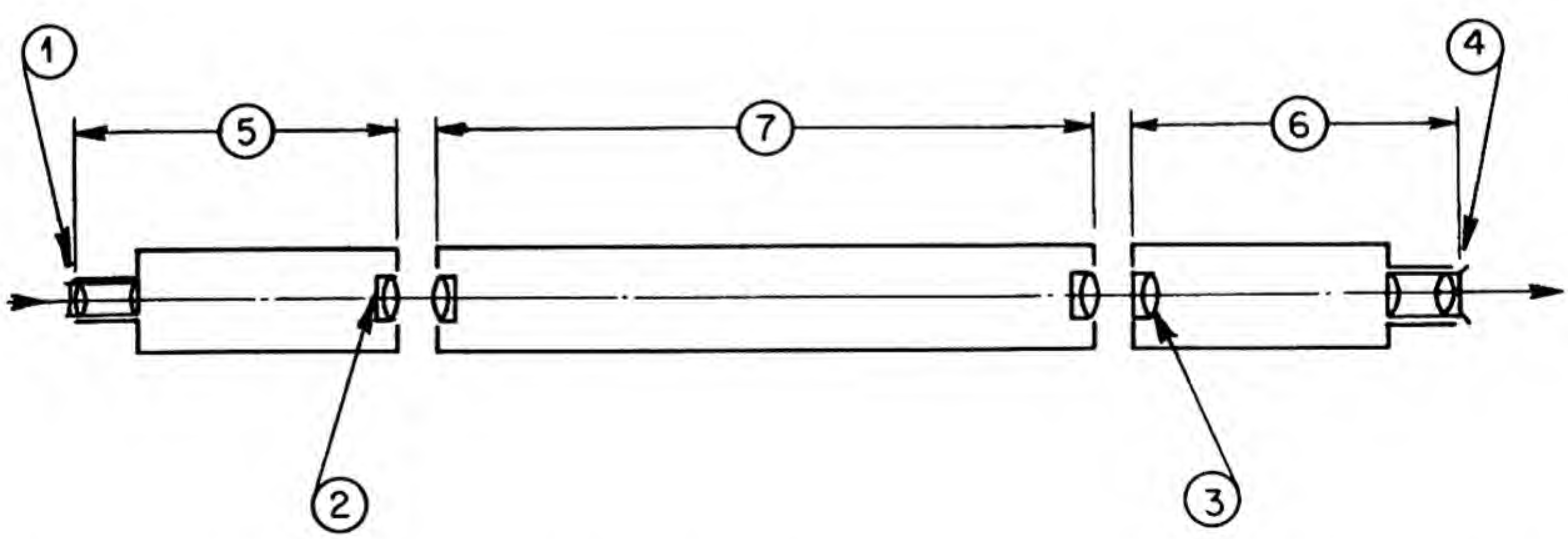


Fig. 3—Scanning sight of Fig. 1 with simple extender. The position of the added extender is shown at 7.

Type 3 (Fig. 5) is simply a tube of water with high-quality plane parallel glass plates at the ends. This will not invert the image, and it increases the field of view by a factor of approximately four-thirds.

Type 4 (Fig. 6) is a tube of water with a pair of achromatic lenses for windows. The length of the water column must be equal to the sum of the focal lengths multiplied by the index of refraction of the water. This type, like type 1, inverts the image but does not change the magnification. The use of lenses increases the field of view, and there is an additional increase of four-thirds due to the presence of the water.

1.2 Scanning Element. A periscopic train of lenses may be said to move the eye from the exit end to the entrance end of the system, with a field of view determined by the characteristics and separations of lenses. If a large field of view must be seen, some sort of scanning element must be placed at the entrance end of the system.

In conventional periscopes this is usually a prism or set of prisms. If only an annular space must be scanned, a right-angle prism is sufficient, provided mechanical means is supplied to rotate it about the axis of the periscope. This type of scanning head, shown in Fig. 7, was used in older submarine periscopes to scan the horizon. Customarily, the prism was fastened to the periscope, and the whole instrument was rotated about its optical axis.

If, in addition, the same sort of prism is provided with a motion of 45 deg about an axis parallel to its refracting edges and perpendicular to the axis of the periscope, the observer may scan an object space over a solid angle of 2π or more.

Prisms of glass are subject to coloration (see Papers 3.1, 3.2, and 3.3) by high-energy radiation, and therefore substitutes must be provided or else frequent replacements must be made. One substitute is a prism of plastic such as Lucite. Even with large amounts of radiation, Lucite becomes only faintly yellow. The techniques of polishing flat or molding optically isotropic blocks are not yet well developed, but much is expected in the near future. Lucite becomes soft at relatively low temperatures, but other harder plastics are also being investigated.

Another substitute for the glass prism is the metal mirror. Prisms have been largely used in conventional optical construction because satisfactory mirrors could not be made previously. Mirrors may be of Stellite, stainless steel, speculum metal, or aluminized, platinized, or silvered glass; at the time of writing, preference was in the order given. An objection to the block-metal mirror is that it may not hold its shape; stainless steel is a serious offender in this respect. To overcome this, it is becoming customary to mount thin metal mirrors in massive blocks of alloy such as Wood's metal or lead. At the time

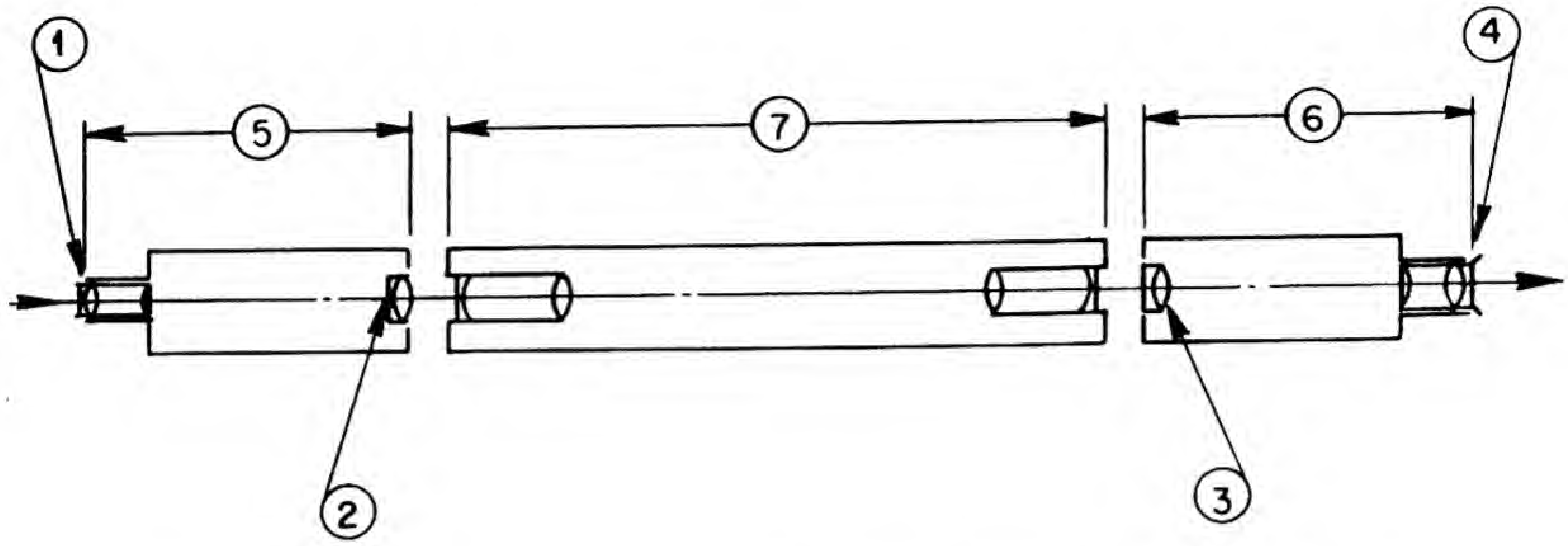


Fig. 4—Periscope scanning sight with special extender (7).

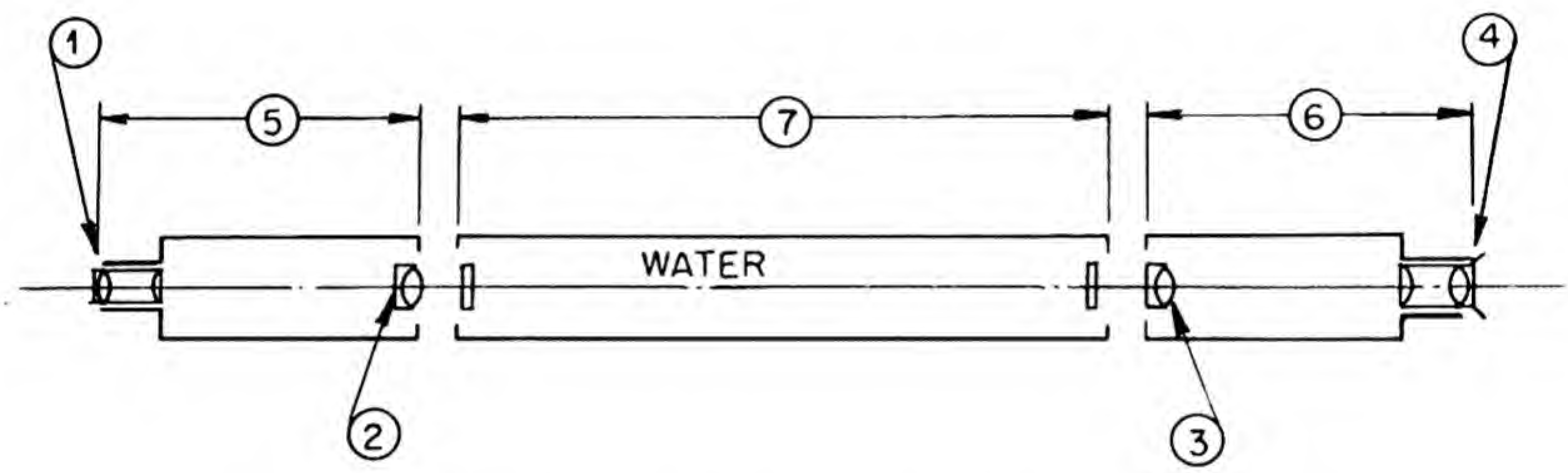


Fig. 5—Periscopic sight with simple water-cell extender.

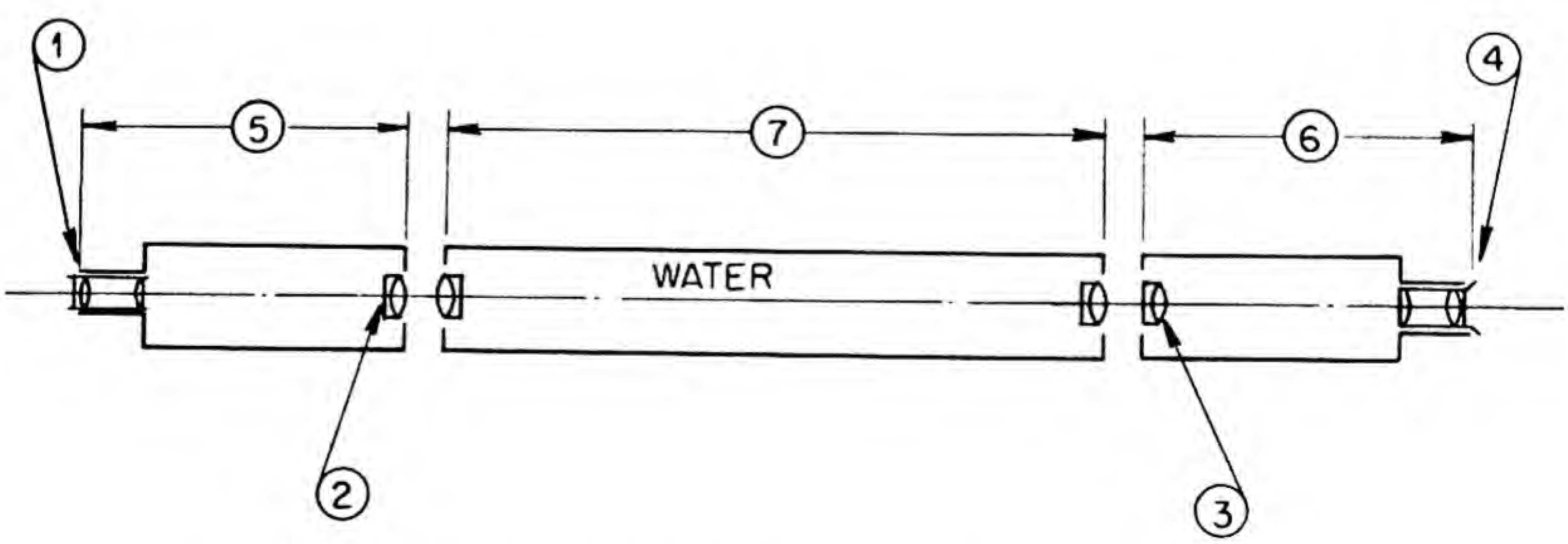


Fig. 6—Periscopic sight with lens-type water-cell extender.

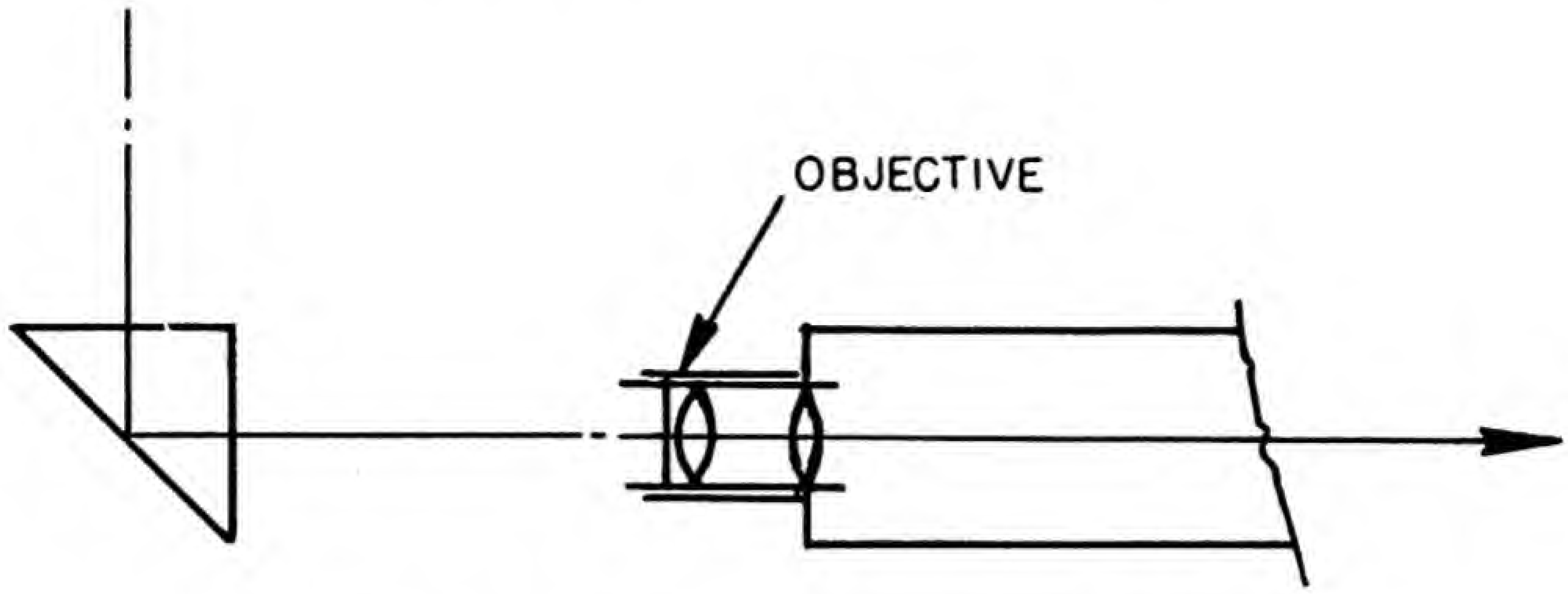


Fig. 7—Prism-type scanning element.

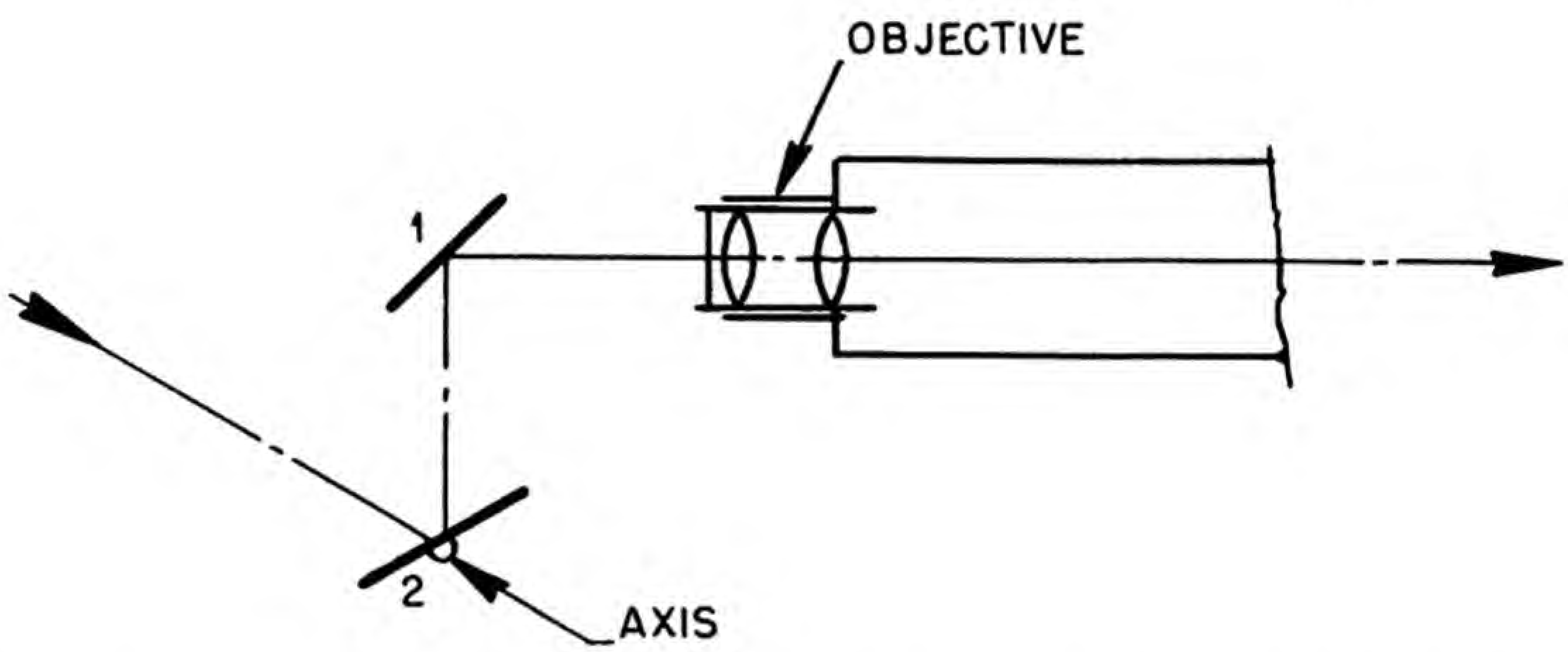


Fig. 8—Dual-mirror scanning element. Mirror 1 obstructs view of rotating mirror 2.

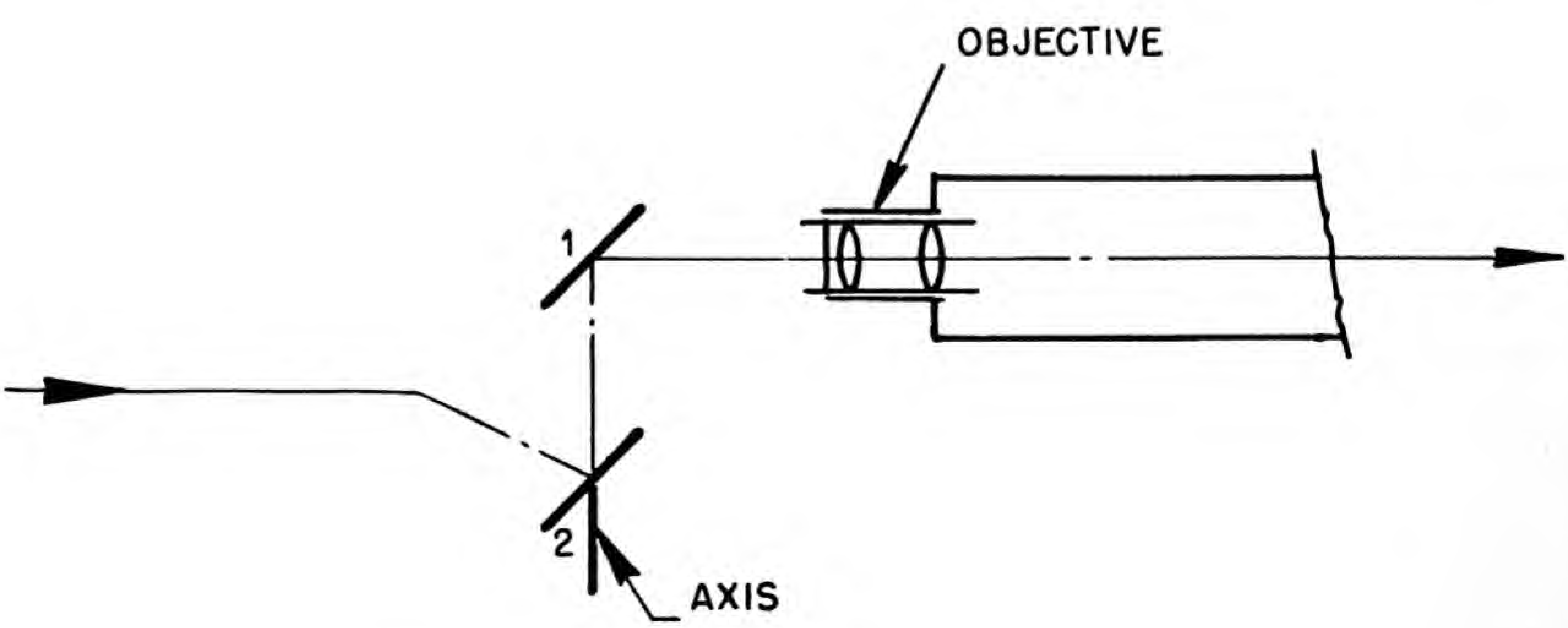


Fig. 9—Full-field dual-mirror scanner.

of writing, however, relatively small mirrors of Stellite ⅛ to ¼ in. thick had been found to retain their flatness.

An objective to the mirror scanner is shown in Fig. 8, which illustrates a pair of mirrors with the second turning about an axis perpendicular to the optical axis of the periscope and lying in the face of the mirror. It is seen that the first mirror obstructs the field of view. If, instead, the second mirror is turned about an axis perpendicular to the optical axis and at 45 deg to its face, as in Fig. 9, there are both advantages and disadvantages. An advantage is that this mirror may be turned through an angle of 180 deg or more with no obstruction of view. (In fact, if it is placed far enough to one side of the periscope, an unobstructed view may be had over 360 deg, and consequently the observer may look directly back at himself.) A serious disadvantage is that as this mirror is turned the image turns over, and therefore objects other than those directly in front of the periscope will appear to be lying on their sides or at an unusual angle. In many cases this can be tolerated. Where it cannot, a compensating device known as a "Dove prism" must be inserted at a convenient place in the optical path, as illustrated in Fig. 10, and turned so as to keep the view normally upright. The motion of this Dove prism must be geared to that of the mirror. The mechanism is expensive and must be precise. Wherever possible, when this mirror arrangement is adopted, the Dove prism should be omitted, and the rotatory motion of the view should be tolerated.

Obviously the prism and mirror arrangements described above are not the only ones possible. They may be set at angles other than 45 deg to the optical axis of the periscope; both mirrors may be turned if desirable; one or both may move on cams or slides instead of on fixed axes; or a single mirror may be used. In fact, with a little ingenuity a design satisfactory for any particular case may be devised.

1.3 Scanning Control. The scanning mirror is operated by a section of spur gear against the circumference of which a thrust or pull is applied by a rod which runs the length of the instrument. This is operated by a turn button inscribed with an angular scale near the eye. It can be mounted wherever described in order to place it within convenient reach of the operator.

1.4 Baffling of Radiation. Baffling of radiation may be accomplished in several ways. A twofold purpose is to be served: (1) to protect the observer and (2) to protect lenses and other glass parts of the periscope itself. The observer is most easily protected by introducing bends into the instrument, so that the light passes along a labyrinth with adequate shielding material (lead, paraffin wax, water, concrete, steel, etc.) about it. The second purpose is more difficult

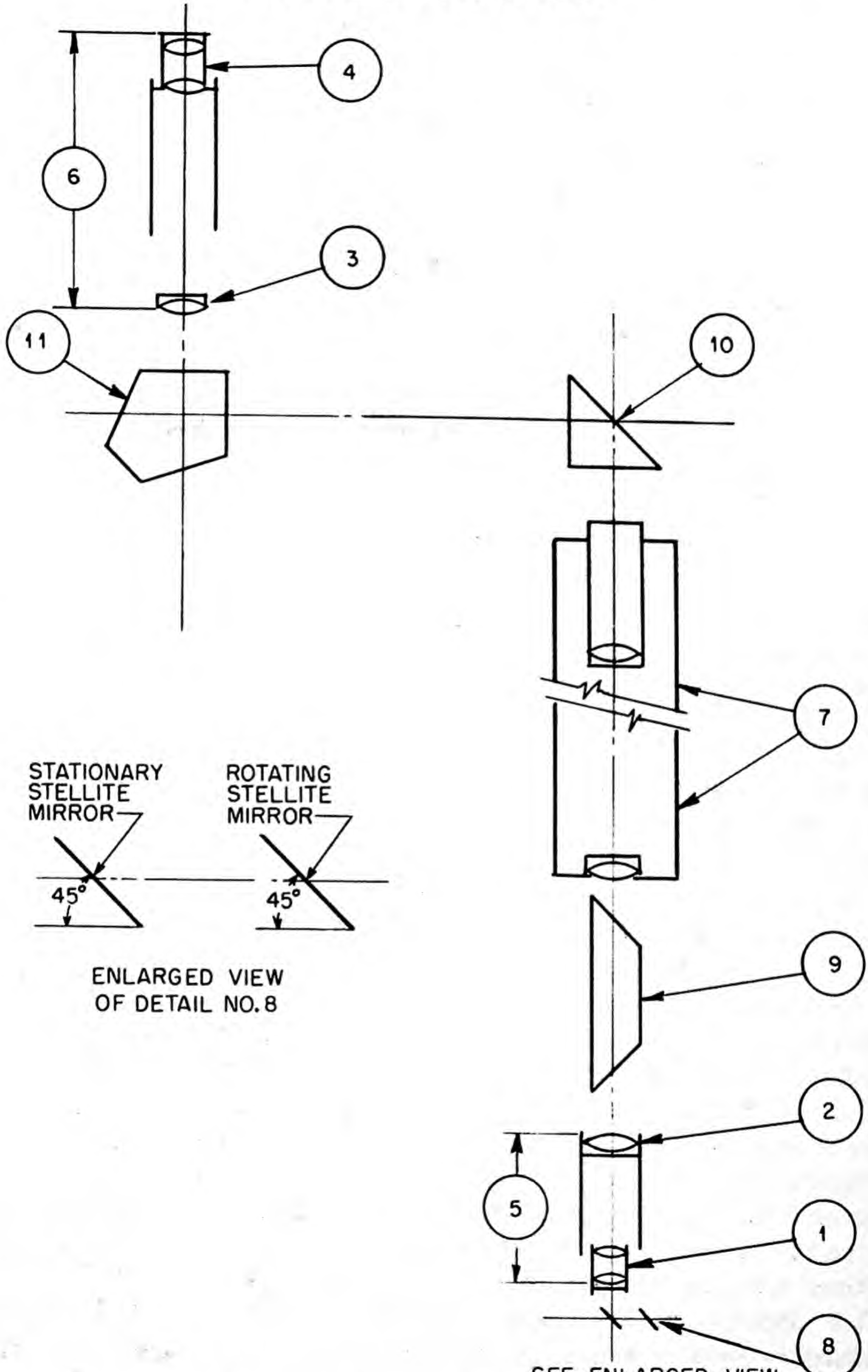


Fig. 10—Schematic diagram of complex periscope incorporating full-field mirror scanner (8) with associated compensating Dove prism (9) and radiation-baffling right-angle turns with reflecting prisms (10 and 11). (Other numbers refer to periscopic elements identifiable with other periscopic sights already described.)

to accomplish. A partial though not entirely satisfactory protection for the lenses is to use mirrors for scanning and to surround them with lead and wax, allowing only the required channel for those light beams which are actually transmitted by the periscope. Fortunately, the volume occupied by these light beams is relatively small. Figure 11 is a schematic drawing illustrating the way in which rays from any object enter the periscope, all passing through the entrance pupil of

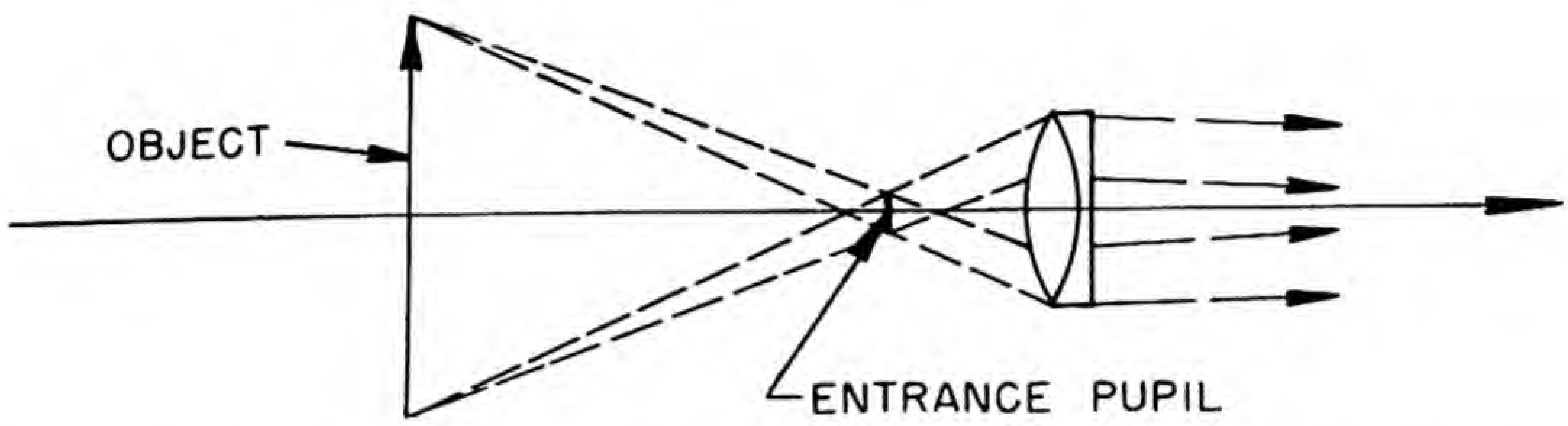


Fig. 11—Entrance pupil of periscopic system. The position and size of the entrance pupil are dependent on other optical elements not indicated.

the system. The entrance-pupil size and location are determined by the character and separation of the lenses and other diaphragms. (An image of the entrance pupil is the exit pupil, at which the eye must be placed for the widest angle of view. The most satisfactory location for the scanning prism or mirror is at the entrance pupil.) Although shielding may thus completely screen all glass parts from direct radiation, there is not a very thick shield about the objective of the periscope, and some scattered radiation may reach it.

One interesting adaptation of the shielding and scanning principles described previously is the slug inspector,[1] designed for inspecting slugs. The optical train of this instrument is illustrated in Fig. 12.

The water tubes illustrated in Figs. 5 and 6 and those lenses nearer the eye may be used as radiation baffles to protect personnel. The water tubes are not entirely satisfactory because the water may eventually become colored and must be replaced. Also, in a vertical position, some provision must be made to sweep sediment and bubbles from the lenses or windows at the ends of the water tubes.

2. GENERAL-SERVICE SCANNING SIGHT

A simple instrument constructed on the principles discussed here has been devised for general service. In external appearance it consists of two metal tubes, each about 12 to 15 in. long. These two

tubes can be provided with a connecting tube of any desired length to extend the instrument from a length of about 30 in. to about 6 ft. If desired, this connecting tube may be telescopic in order that the length

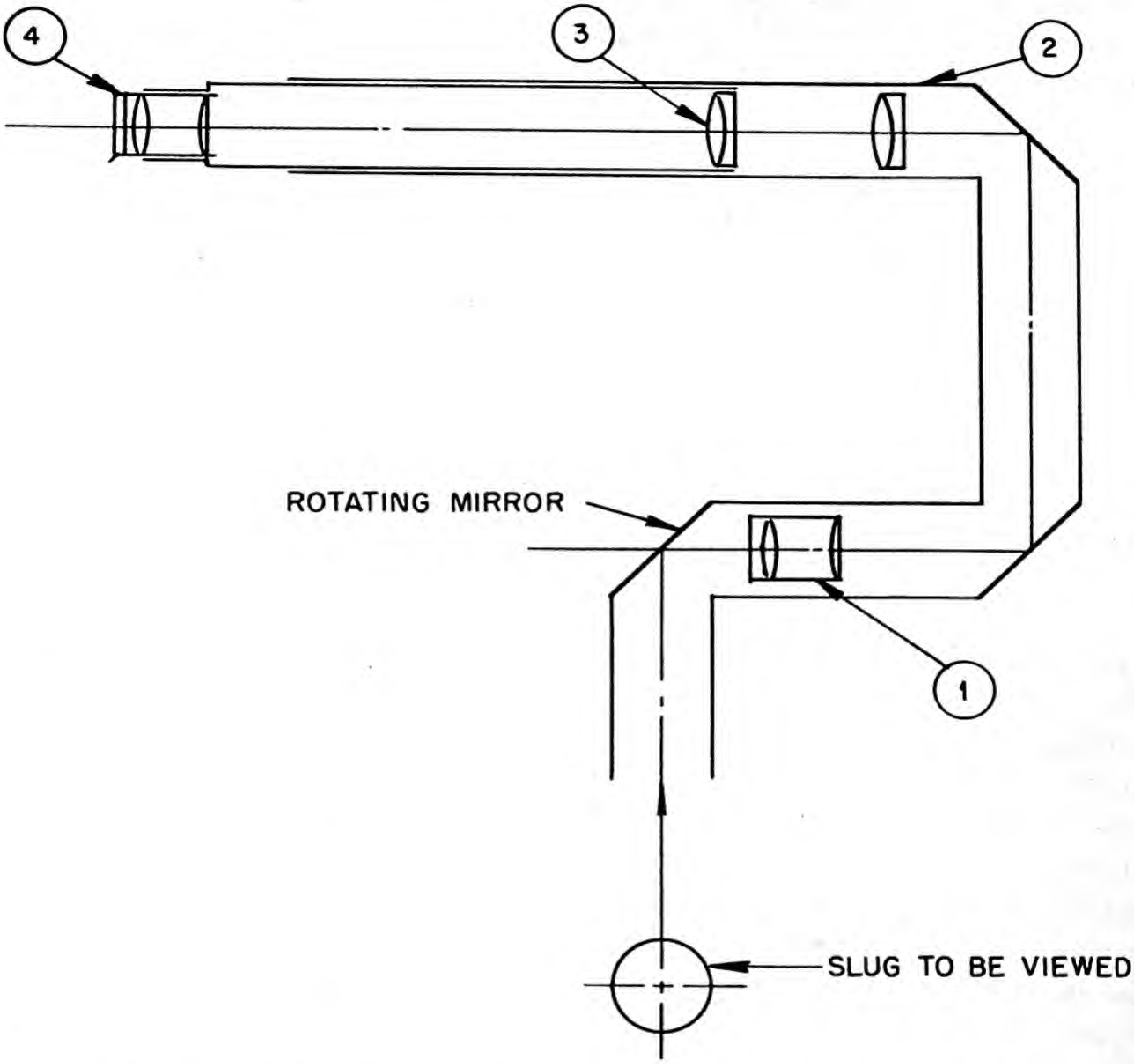


Fig. 12—Application of a simple periscopic sight to a slug viewer.

may be changed at will. For lengths greater than 6 ft, the field of view decreases rapidly, and special extending lens systems may be provided.

The instrument is provided with a single Stellite scanning mirror. Normally this will enable the observer to scan an area about 30 deg wide (the angle of view of the periscope) and about 140 deg long. This area lies to one side, as shown in Fig. 13. Other scanning systems of prisms or mirrors can be provided.

It should be emphasized that the optical parts of this standardized scanning sight can be adapted to mechanical forms other than the one indicated.

If suitably designed, this scanning sight can be focused on objects over a wide range of distances from 1 or 2 ft to infinity. In some military periscopes, where it is inconvenient to move the eyepiece for

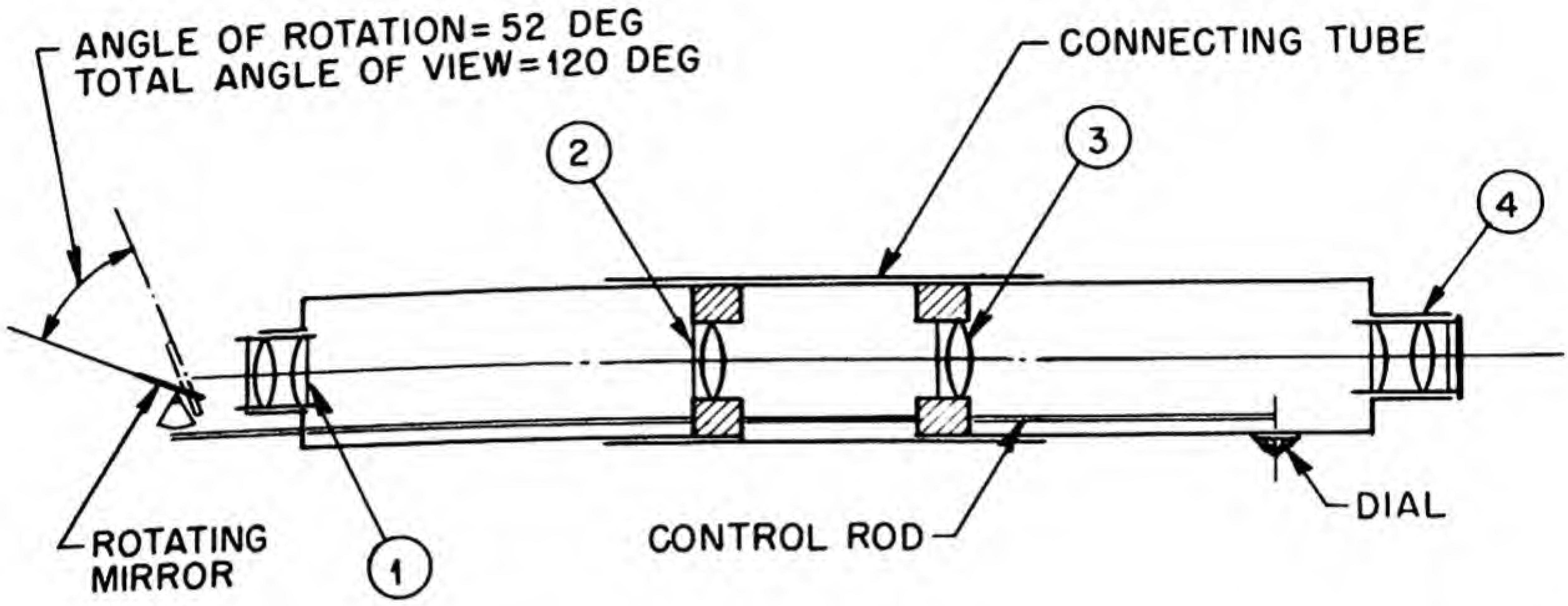


Fig. 13—Standard periscope employed in the general-service scanning sight.

focusing, the objective is a compound element in which focusing is done by shifting one lens along the axis. Similarly, some submarine periscopes are constructed with one objective system for distance and one for near objects, one being shifted out of the field and the other being brought in as desired. In developing the present instrument, the aim was to build a usable and convenient scanning sight, using not too many optical parts, with as wide a range of application as possible. For this reason the focusing is done by moving the eyepiece in or out as desired. The focusing mechanism is a helical groove with a steel sliding arc.

For nearby objects, higher power than 2 or 3 is rarely necessary. The general-utility scanner can be furnished with either or both of two eyepieces. One gives a magnification of unity; the other gives a magnification of 2½.

REFERENCE

1. George S. Monk, Report CE-2384, Nov. 17, 1944.

Paper 1.2

COMPARATIVE TESTS OF PERISCOPIC EXTENDERS*

By George S. Monk and Walter Wallin

1. INTRODUCTION

In a periscopic sight (see Paper 1.1), it is desirable that the optical path, which affords a clear channel for radiation (see Papers 3.1 and 3.2), be as small in cross section as possible. Studies of extended periscopic systems have been made to restrict this cross section and to retain at the same time a field of view as large as possible. For these tests there were available: (1) erector lenses of stepped-up focal lengths, (2) a pair of Galilean systems, each of zero power, which, when placed in train about 1 meter apart, serve as an extender, and (3) achromatic lenses of approximately 50- and 100-cm focal lengths, which may be used in combination as extenders.

2. WAYS OF MAINTAINING THE FIELD

2.1 Second Erector Lens. The second erector lens may be enlarged in order to cover the diagonal rays. The advantage in this method is that the number of optical parts is not increased. On the other hand, with present methods of low-reflection lens coating, an increase of two or three in the number of lenses does not seriously affect the light transmission. Also the apertures must necessarily be larger, especially for the second erector. This is a disadvantage because it necessitates a channel of larger diameter through which harmful radiation might pass. A second disadvantage is that as the diameter is increased the cost of an achromatic lens rises much faster.

2.2 System of Galilean Lenses. The size of the second erector may remain constant, and a system of Galilean lenses may be inter-

*This paper is based on Report CT-1351, February 1944.

posed, as shown in Fig. 1. However, this method has few advantages to warrant its use. Although the lenses used are simple and not corrected achromats, each element must be specially mounted. Corrections in a Galilean system of simple lenses are poor, and the field covered is inherently small. In addition, there seemed to be a marked loss of light. An advantage over the method described in Sec. 2.1 is that the diameters may be kept down. Another advantage is that the erectness of the image is maintained.

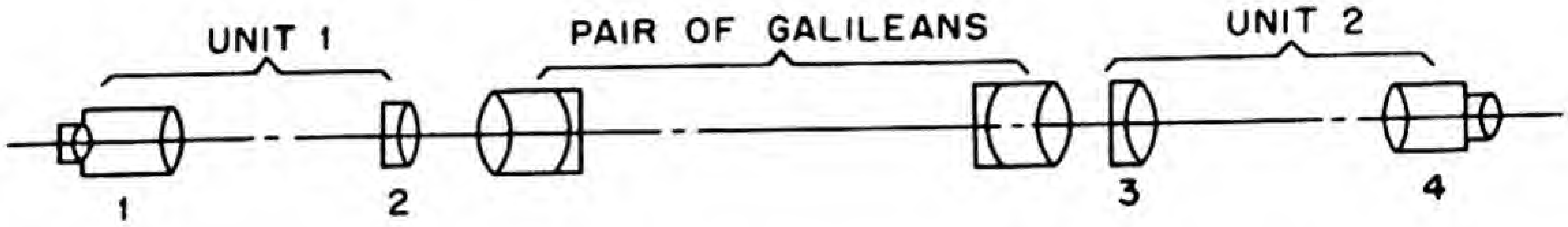


Fig. 1—Periscopic system; second erector. (1) Objective lens. (2) First erector lens. (3) Second erector lens. (4) Eyepiece lens.

2.3 Telescopic Extender. The second erector may be kept the same, and a telescopic-extender system of two achromats may be interposed, as shown in Fig. 2. The prime advantage of this method is that the diameter of the tube may be kept down. This is helped by putting a field lens, a single biconvex element, at the focal position between the extender lenses, as shown in Fig. 3. Thus the diameter of the second achromatic lens in the extender system may be kept down. A second advantage is that the exact placing of this extender is, over a considerable range, quite unimportant because the rays from any object point entering and leaving it are parallel. A third advantage is that this type of extender, since it is telescopic, may be made the means of obtaining magnification of the image, which otherwise would have to be obtained in the rest of the system. For instance, an extender 150 cm long with a power of 2 can be made with a first lens having a 100-cm focal length and a last lens having a 50-cm focal length. Thus a standardized periscopic sight can be used and, for an especially long instrument, can be simply extended to the required length. If one such extender is not sufficient, more may be used in train.

One objection to the use of a single extender is that the image will be completely inverted. However, the total number of inversions can be adjusted, if desired, to yield an uninverted image.

2.4 Water-filled Extender. For completeness it should be noted that an extender filled with water can be used to keep the diameter small. This will also tend to increase the field of view because the

focal length of a lens in water is 1.33 times that in air. The optical difficulties are negligible, but the construction and maintenance problems are troublesome. Water in an optical system must be the purest obtainable and free from subsequent contamination. A commercially tinned tube used in one periscope was a dismal failure. On the other hand, an experimental 40-in. water-filled tube coated with Plicene wax was still extraordinarily clear after seven months, and similar successes are recorded with tubes tinned in the laboratory.

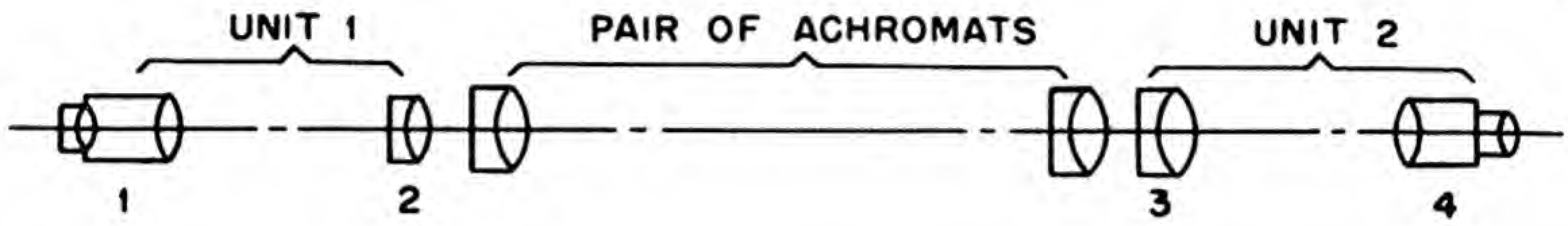


Fig. 2—Periscopic system; eyepiece lenses. Lenses are the same as identified for Fig. 1.

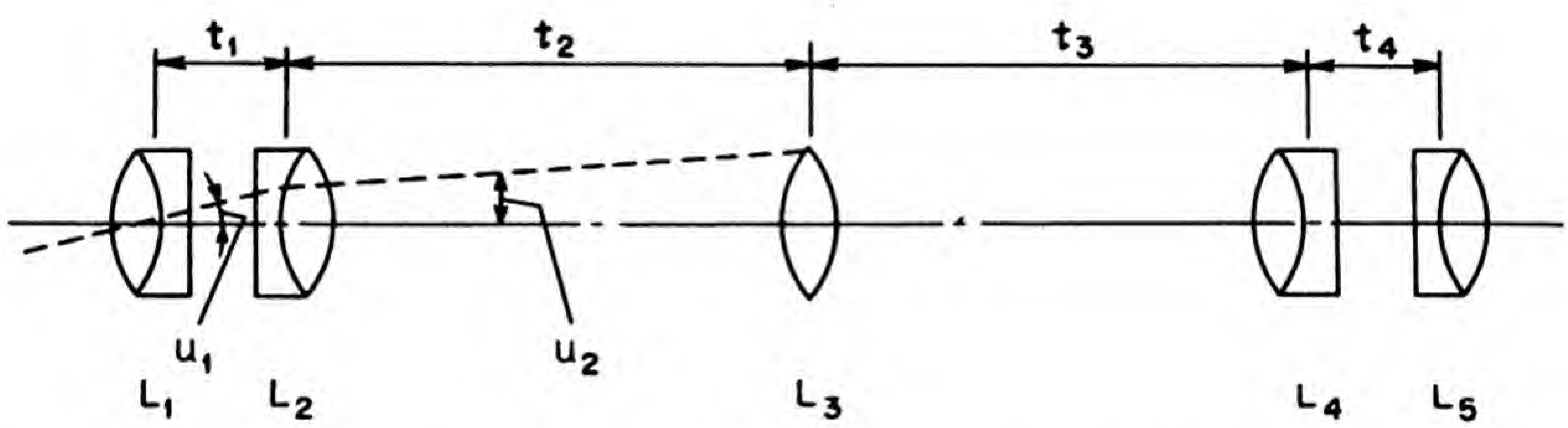


Fig. 3—Telescopic extender. L_1, first erector lens. L_2, first extender lens. L_3, extender field lens. L_4, second extender lens. L_5, second erector lens.

3. THEORETICAL DISCUSSION

In telescopic systems of great tube length it is advisable to make the chief ray crossings coincide with certain of the lenses and to make the image-forming ray crossings for axial points coincide with others. This is desirable for two reasons. First, it makes for better correction. The bundle of rays that crosses at the center of a lens is not refracted; thus all the correction of that lens can be given to the other bundle. This is a theoretical consideration that may not be of importance in a system having an aperture ratio as low as that considered here. The second reason is a practical consideration. By adhering to

this system it can be assumed that incident and emergent image-forming bundles are parallel, while the first and last lenses are pupil lenses. Then a standard design of telescope doublet can always be proportioned to the appropriate focal lengths in designing new extenders.

The simplest telescopic extender is shown in Fig. 3 and discussed in Sec. 2.3. For most Project purposes this type of extender is preferred.

The chief ray for the edge of the field is shown as a dashed line, and the image-forming rays for the center of the field are indicated by a solid line. By assuming that the maximum allowable lens diameters are fixed and that the first extender lens is located so close to the first erector that the refraction of the chief rays is negligible,

$$t_2 = \frac{D_3}{(2 \tan u_2)} \tag{1}$$

If the magnification of the extender system is unity,

$$t_2 = 2f_3 \tag{2}$$

If no bending of the image-forming rays is to take place at the field lens L_3,

$$f_2 = t_2 = f_4 \quad \text{(unit magnification)} \tag{3}$$

Thus the over-all length cannot be increased to more than $D_3/\tan u_2$. If the magnification is greater than unity, a shorter tube results or the diameter D_3 must be increased, a condition to be avoided.

Consider the case where t_1 is large, that is, where the extender is some distance away from the first erector. Then the chief rays will strike L_2 at such a height that they will be refracted appreciably, thereby lowering their height on lens L_3. By simple optical theory and by assuming that the angle is small enough so that it can be substituted for its tangent,

$$\begin{aligned} h_3 &= h_2 + t_2 u_2 \\ u_2 &= u_1 - d_2 h_2 \end{aligned} \tag{4}$$

where h_i = height of the ray on the *i*th lens
t_2 = space between lens 2 and lens 3
d_2 = power of lens 2 ($d = 1/f$)
u_i = slope angle of the ray in the *i*th medium

Then

$$h_3 = h_2 + t_2(u_1 - d_2h_2) \tag{5}$$

which, when transposed, gives

$$h_2(1 - t_2d_2) = h_3 - t_2u_1 \tag{6}$$

With h_3, t_2, and u_1 all fixed, Eq. 6 is a rectangular hyperbola in h_2 and $(1 - t_2d_2)$. The asymptotes are the axes; therefore f_2 cannot equal t_2. This means that the image-forming rays cannot be made to cross at the center of the field lens. Since the field lens L_3 is necessarily a simple lens, the rays from an object point on the axis should cross it at the axis. Thus there is a restriction on the location of the extender with regard to the first erector. Theoretically, the best results can be obtained only by limiting the extender length to a value determined by the field angle and the field-lens diameter. In the case considered here, this limiting value is less than the required length; therefore results that fall short of the best value must be accepted.

An investigation of another solution is under way, which should allow the desired extension and field to be obtained with a single extender and with no increase in diameter of the field lens.

Paper 1.3

THE ERECTING OBJECTIVE MAGNIFIER*

By George S. Monk

ABSTRACT

A means is suggested for increasing the magnification of a periscopic sight and at the same time retaining a maximum number of its desirable original characteristics. Advantages of this magnifier over other types are pointed out.

It is often desirable to get larger magnification with a periscope or sight-type instrument. The basic design is shown in Fig. 1, Paper 1.1. The whole instrument, consisting of objective element, first erector, second erector, and eyepiece, is usually designed to give a magnification of unity, although this magnification can be increased by increasing the ratio of the focal lengths of the first and second erectors.

Another means of increasing the magnification is to substitute for this eyepiece an eyepiece of higher power. The principal objections to this are that such an eyepiece has a small field, the light intensity is diminished by magnification, and there are mechanical difficulties in substitution. Also, it is frequently true that the optical definition of the periscope is not good enough to stand the increased magnification. Substitution of a second eyepiece, which is otherwise satisfactory, rarely increases the magnification by more than a factor of 2 or 3, and the accompanying loss in definition is serious.

It is obvious that another means by which the magnification may be increased is to remove the objective element and the first erector entirely from the system, leaving a single telescope. Not only is this usually mechanically difficult, but the resulting image will be inverted.

* This paper is based on Report CP-2170, Sept. 30, 1944.

Another way to increase the magnification is to add an element E to the objective element so that E and the objective element together constitute a system having the same focal length as the first erector. If, at the same time, the image position given by the objective element alone were not shifted, the resulting combination E, objective element, and first erector would be a celestial telescope of unit power (shown in Fig. 1). If a third requirement is also fulfilled, and E is such an element that it does not change the inversion of the image, then the entire resulting instrument will give an erect image just as does the original unmodified periscope.

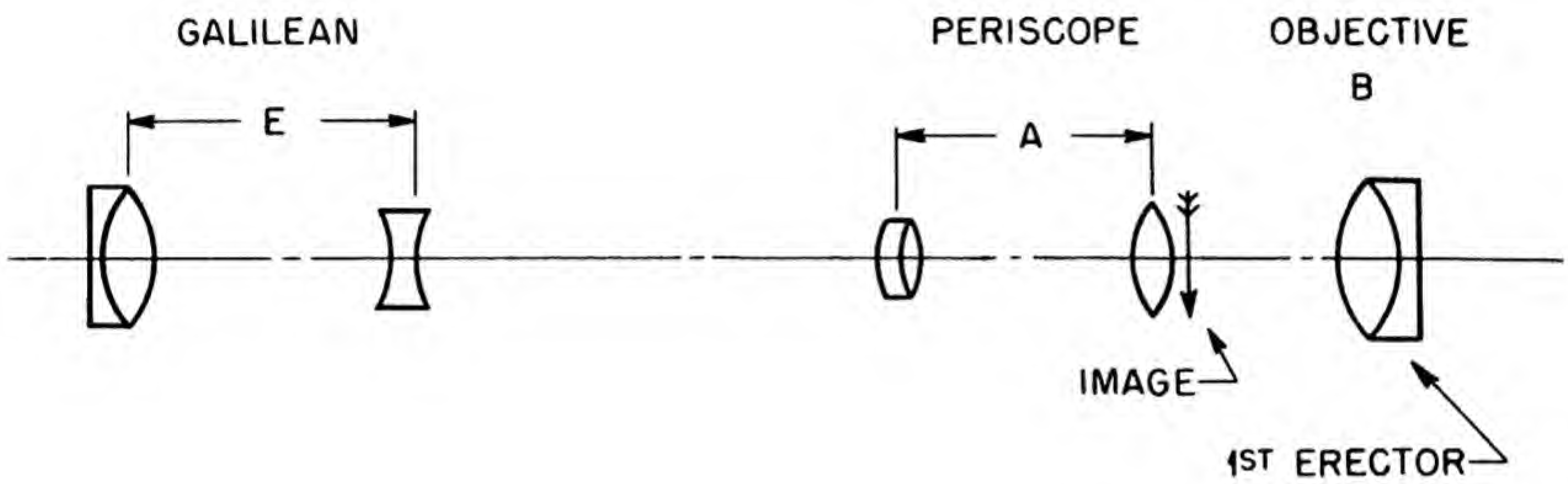


Fig. 1—Periscopic objective with erecting magnifier in position.

The three requirements stated in the preceding paragraph obviously indicate that the element E to be added must be an erecting element. Since the image position of the objective element in Fig. 1 also will vary with the object distance, E must be adjustable in focal length. It was suggested by Edward Bickel that a simple Galilean-type monocular would fill the requirements. One was tried and found to give excellent results, with limitations on adaptability. Walter Wallin advised that it would be difficult to design a Galilean monocular having a magnification factor larger than 4. In some periscopes built for Project purposes, the ratio of magnifications of t_2 alone to the entire periscope is over 12; thus a Galilean of power higher than 4 would be needed to make the power of t_1 equal to unity. This seems to be a limitation on the use of device E.

In actual practice, however, the results are very good. A monocular with an objective 3 cm in diameter and 12 cm in focal length, having an over-all length for infinity of about 8 cm, was placed in front of an optical system designed for use in an underwater binocular periscope. Without the monocular this system has a magnification of 3 for an object placed 15 cm in front of the periscope. With the monocular

added the magnification was 9, and the definition was excellent. At the object distance used, points 1/32 in. apart could be resolved.

It would be most desirable to add the Galilean element without altering the position of the final image in the field of the eyepiece, so that no refocusing would be required. This can be done only if all objects to be looked at are far away or at some definite distance. If the periscope is used to view near objects at different distances, some refocusing must be done.

A marked advantage of this magnifier over other types, such as high-power eyepieces, is that it increases the light-gathering power of the periscope. For instance, in the trials made, the field lens of the periscope objective had a diameter of 21 mm, and the field lens of the Galilean had a diameter of 30 mm. The slight shift in the exit pupil caused no difficulty to the observer.

In most cases, commercially available monoculars may serve well enough, although a form more advantageous for adaptation to Project instruments might be designed. For a binocular underwater periscope an objective with a flat front surface is desirable to avoid the necessity for a flat window.

Paper 1.4

DESIGN OF A KELLNER-TYPE PLASTIC OBJECTIVE*

By Minnie Mrjenovich

ABSTRACT

The design and analysis for a Kellner-type plastic objective of cyclohexyl methacrylate ($n_D = 1.5062$) and styrene ($n_D = 1.5915$) are given. The objective patterned after a Kellner-type glass objective of suitable characteristics for periscopic applications was found to be very satisfactory.

1. INTRODUCTION

An objective of plastics was designed because of the superiority of optical plastics over glass in resistance to coloration (see Papers 3.1 and 3.2) by high-energy radiation. The materials used were cyclohexyl methacrylate (CHM) ($n_D = 1.5062$) and styrene ($n_D = 1.5915$). The dispersion curves for these plastics are shown in Figs. 15 and 16.

The instrument was to be of the periscopic variety, requiring a small-diameter objective, for examination of near objects. A Kellner-type objective of glass was found to be suitable, and this was used as a prototype in the present design. Details of the glass objective assembly, comprising the doublet achromat and the singlet field lens, are given in Fig. 17.

2. METHOD

In preliminary calculations the equivalent focal length, 40.13 mm, of the glass objective was retained, and it was computed that the entire system would give an entrance pupil about 25 mm in front of the

*This paper is based on Report CP-3083, June 30, 1945. The Kellner-type plastic objective described in this paper was designed by Elaine Sammel Palevsky and Minnie Mrjenovich under the supervision of W. Wallin.

objective and about 6 mm in diameter. Then a paraxial ray was traced through the glass system. The data so obtained gave values of θ_i, where θ_i is the product of the slope angle, in radians, of the paraxial ray and the index of refraction of the *ith* medium. These values of θ_i were used in tracing a paraxial ray through the equivalent plastic system because the aberrations are direct functions of the θ's, and by keeping the θ's the same the minimum change in aberrations is made.

Third-order approximations and exact values of the Seidel aberrations of both glass and plastic objective assemblies were calculated. These were obtained by having the object at infinity and making chief-ray tracings and exact triangulations of paraxial and chief rays for n_C, n_F, and n_D indices through both the plastic and glass systems. The chief ray was made to strike the first lens at the full height of the entrance pupil (see Fig. 1). A comparative discussion of the results follows.

2.1 Aberrations. The difference in focus of the different colors of white light, $\Delta a'$ (Fig. 2), is due to the refractive index of a lens varying according to the color of light.

(a) Longitudinal Chromatic Aberration of Focal Position. In Fig. 3, first-order $\Delta a'$ is plotted along the axis, and exact $\Delta a'$ is plotted at full height of the entrance pupil.

First order	Plastic	Glass
$\Delta a'_F$	0.356	-0.0071
$\Delta a'_C$	0.127	0.0296
Exact		
$\Delta a'_F$	-0.0803	-0.3620
$\Delta a'_C$	-0.2923	-0.3718

(b) Lateral Chromatic Aberration of Magnification. The exact value of $\Delta y'$ for plastic is 0.1264, and for glass it is 0.0972.

The difference in intercept length of the paraxial and extreme marginal rays, $\Delta a'$ (Fig. 4), would converge on a single-point focus.

(c) Longitudinal Spherical Aberration. In Fig. 3, both third-order and exact values of $\Delta a'$ are plotted at full height of the entrance pupil. The third-order value of $\Delta a'$ for plastic is -0.679, and for glass it is -0.370. The exact value of $\Delta a'$ for plastic is -0.440, and for glass it is -0.371.

(d) Lateral Spherical Aberration. In this case the exact value of $\Delta y'$ for plastic is -0.0510, and for glass it is -0.0276.

Coma affects only image points off the axis (see Fig. 5). An extra axial-point object does not focus at a point; therefore the image point, instead of being sharp, is spread out asymmetrically. The per cent coma for plastic is −0.106, and for glass it is 0.0089. The linear coma, B, for plastic is −0.468, and for glass it is 0.114.

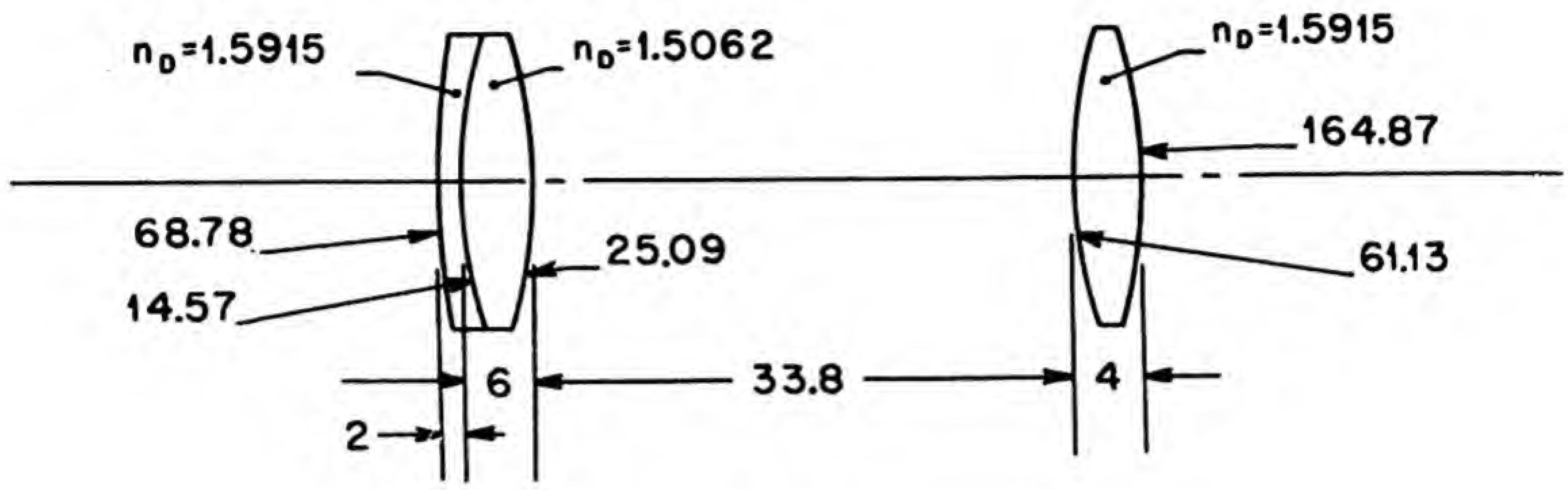


Fig. 1—Preliminary design of plastic objective. All dimensions are in millimeters.

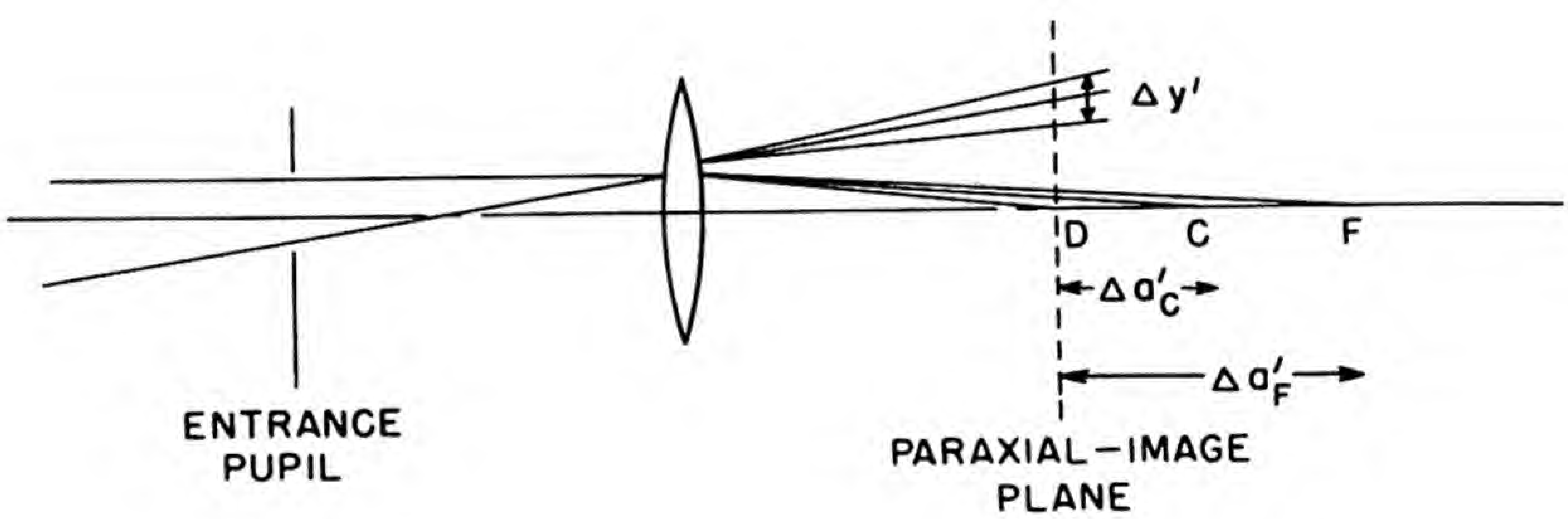


Fig. 2—Chromatic aberration referred to sodium D.

For perfect symmetry and no coma the distance between y′(−h) and y′(O) must be equal to that between y′(+h) and y′(O). The measure of the difference (B) determines directly the true coma of the system; that is, B is the measure in millimeters of the comatic flare. In Fig. 6, X_P is the difference in focus of the center and edge of the field. If the point P is the primary focus on the chief ray of an extreme object point, then X_P is the linear distance measured parallel to the axis in a coordinate system having the paraxial focus as origin. The value of X_P for plastic is 5.79, and for glass it is 1.74.

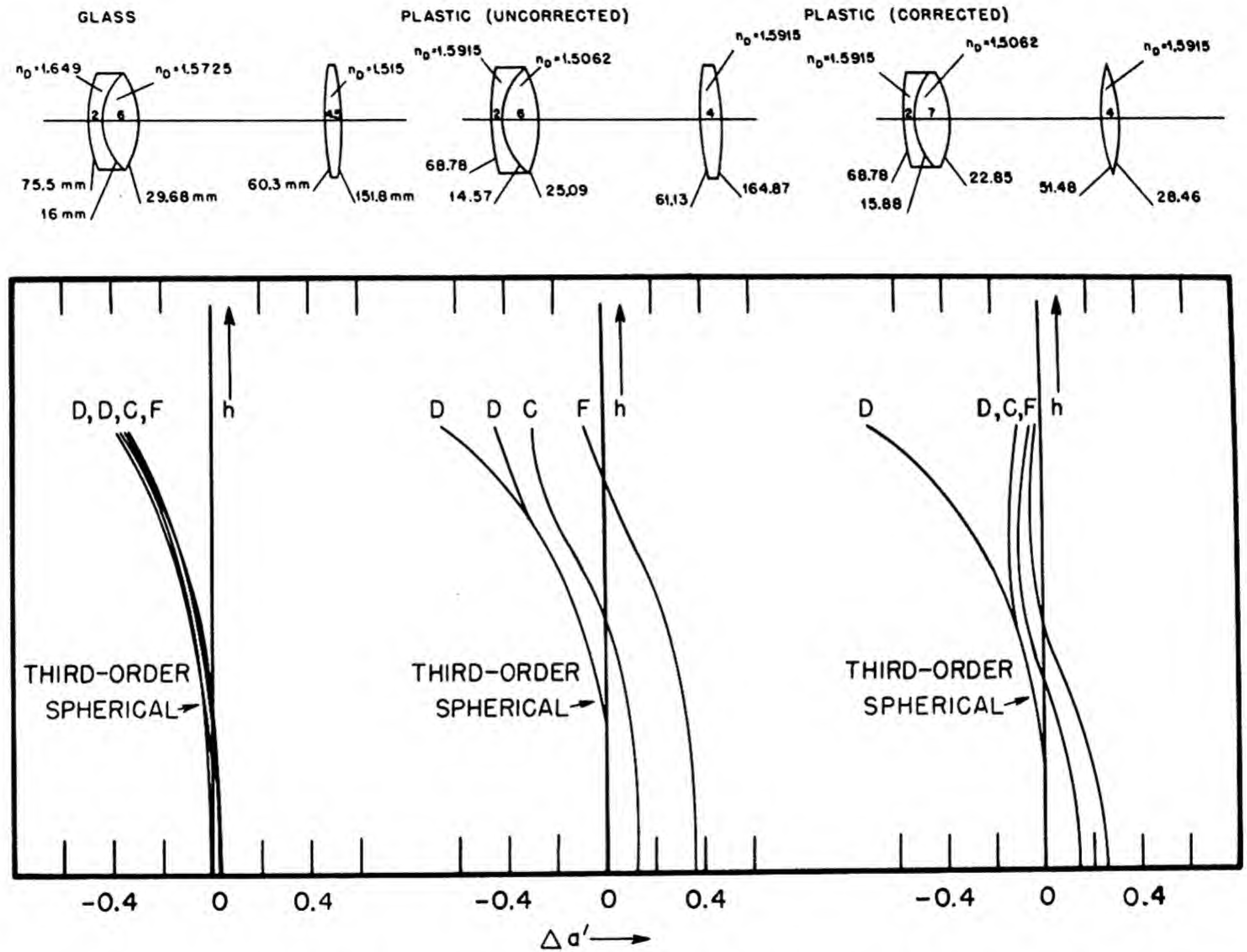


Fig. 3—Glass and plastic (uncorrected and corrected) objective assemblies, with curves for each type showing third-order aberrations.

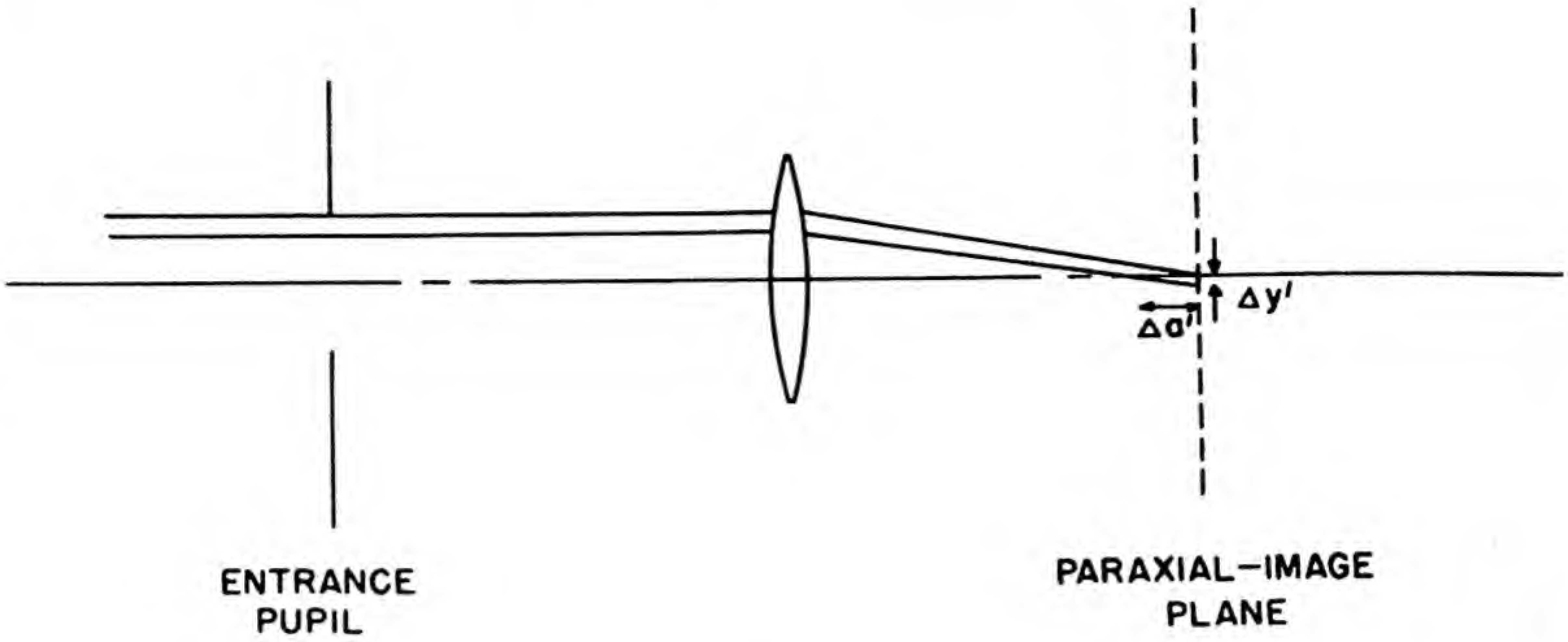


Fig. 4—Spherical aberration.

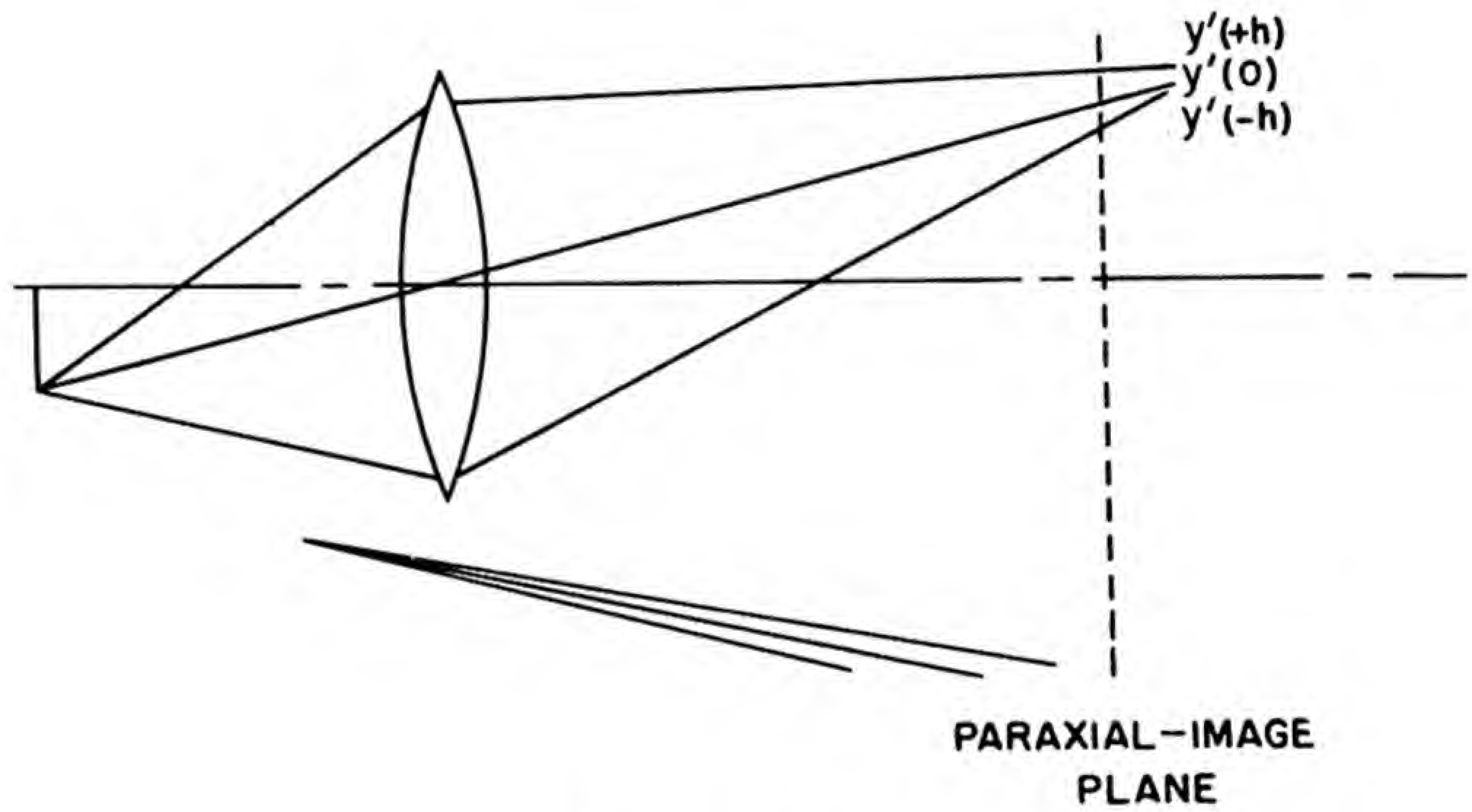


Fig. 5—Coma.

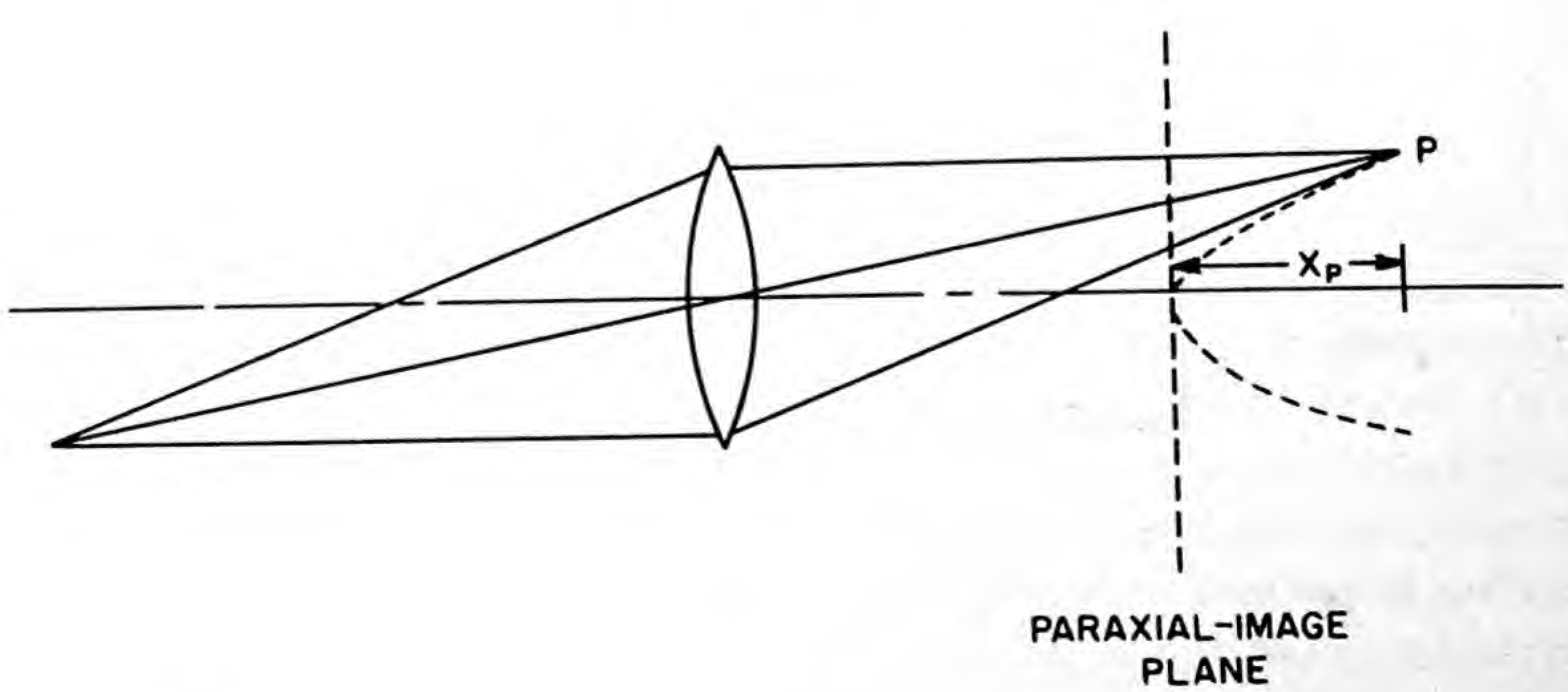


Fig. 6—Primary curvature of the field.

The secondary image (see Fig. 7) of an extra axial point lies on the straight line connecting the object point with the center of curvature of the refracting surface. In this case the value of X_s for plastic is 1.725, and for glass it is 0.283. The value of Y_s for plastic is 0.0454, and for glass it is -0.025.

The point of intersection of the chief ray with the paraxial-image plane is y'. To determine the amount of distortion, two chief rays were traced (see Fig. 8). If there is no distortion, a perfect 45-deg triangle is formed (Fig. 9) when $y'(15°)$ is plotted along the hypotenuse and $y'(15/\sqrt{2})°$ is plotted along the axis. When this is done, the value of $y'(15°)$ for plastic is 11.88, and for glass it is 10.77. The value of $y'(15/\sqrt{2})°$ for plastic then is 7.60, and for glass it is 7.56.

2.2 Corrections. In all computations correcting the objective, the field lens was made of styrene rather than cyclohexyl methacrylate because the former was thought to discolor at a slower rate.

It is readily seen from the aberration values and graphs that longitudinal color must be corrected. From the theory of chromatic aberration it is known that, when corrections are made, the change in $\Delta a'_F$ is about three times greater than the change in $\Delta a'_C$. Figure 3 shows that it would be impossible to bring the first-order $\Delta a'_F$ and $\Delta a'_C$ into coincidence with the first-order D, which is taken as the axis. They both lie to the right of the paraxial D image, and, if $\Delta a'_F$ is made equal to 0, $\Delta a'_C$ would have a large positive value. The best possible correction would be to bring $\Delta a'_F$ and $\Delta a'_C$ as close together as possible.

Lens design theory shows that θ_5 and θ_9 exert the greatest influence on the color. To determine the rate of change in $\Delta a'$ with a change in these angles, a new value of θ_5 was obtained by the color-correction formula:

$$d\theta_5 = \frac{-v_3 v_7 \theta_9}{h(v_3 - v_7)}\, d\Delta a'$$

where $v_3 = \dfrac{n_D - 1}{n_F - n_C}$ styrene

$v_7 = \dfrac{n_D - 1}{n_F - n_C}$ CHM

h = full height of entrance pupil

$d\Delta a'$ = increment of change in chromatic aberration

θ = product of the slope angle (in radians) of the paraxial ray and the index of refraction of the medium it is passing through; the subscripts denote the media whose numbering system is shown in Fig. 10

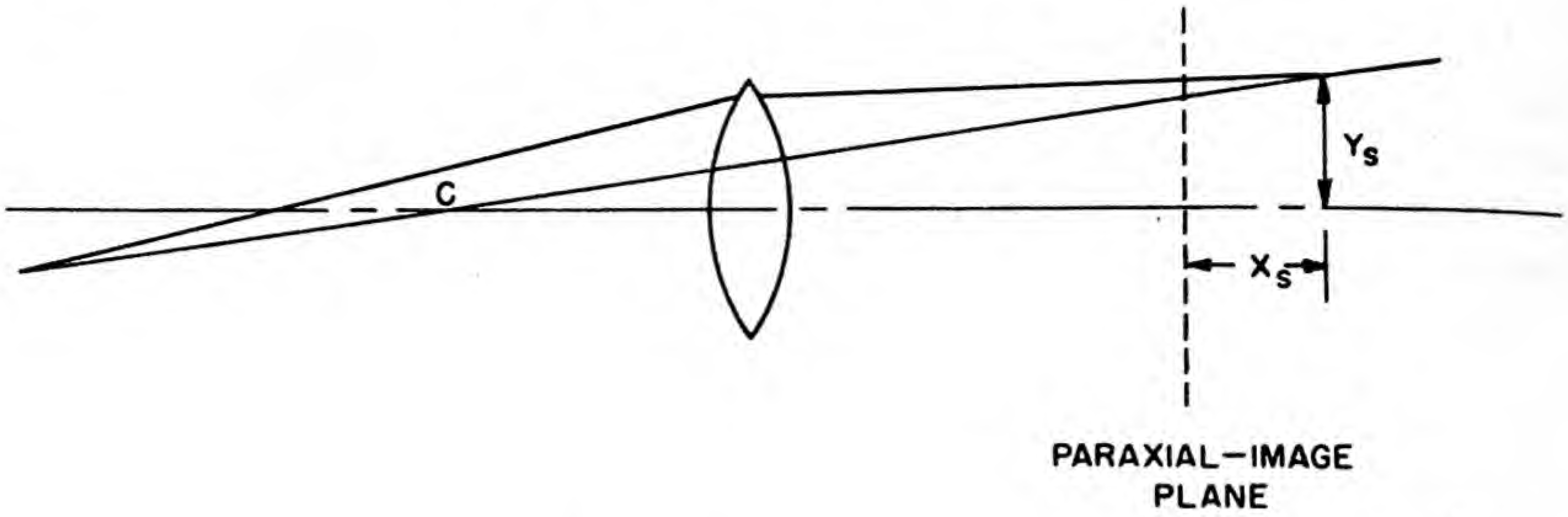


Fig. 7—Secondary curvature.

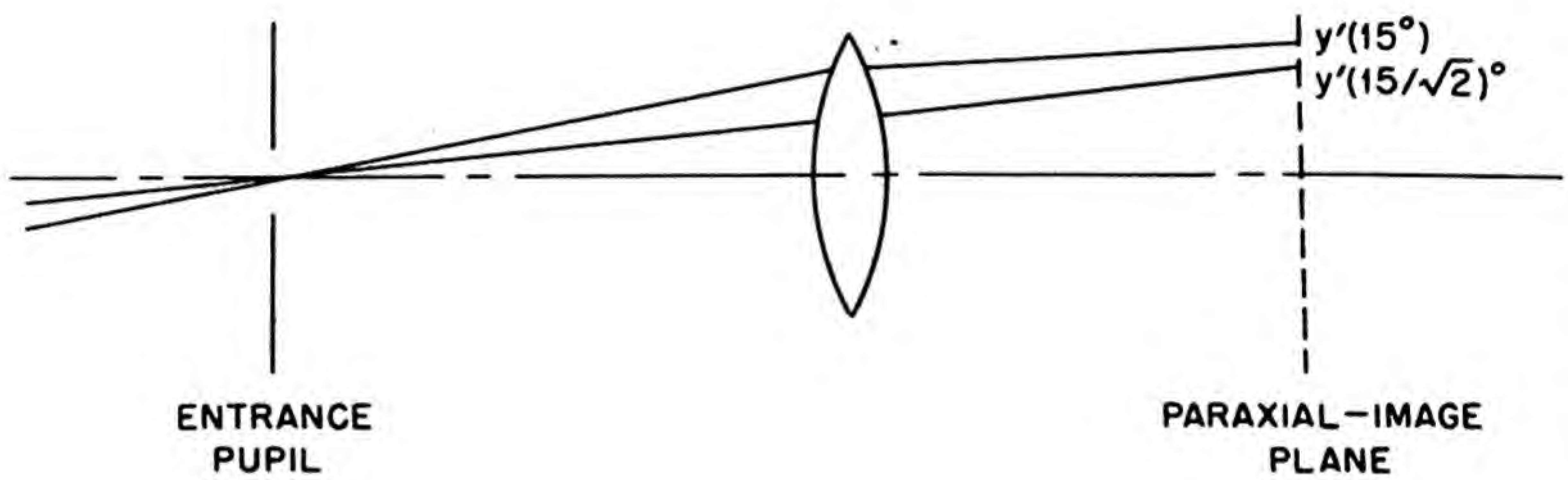


Fig. 8—Distortion.

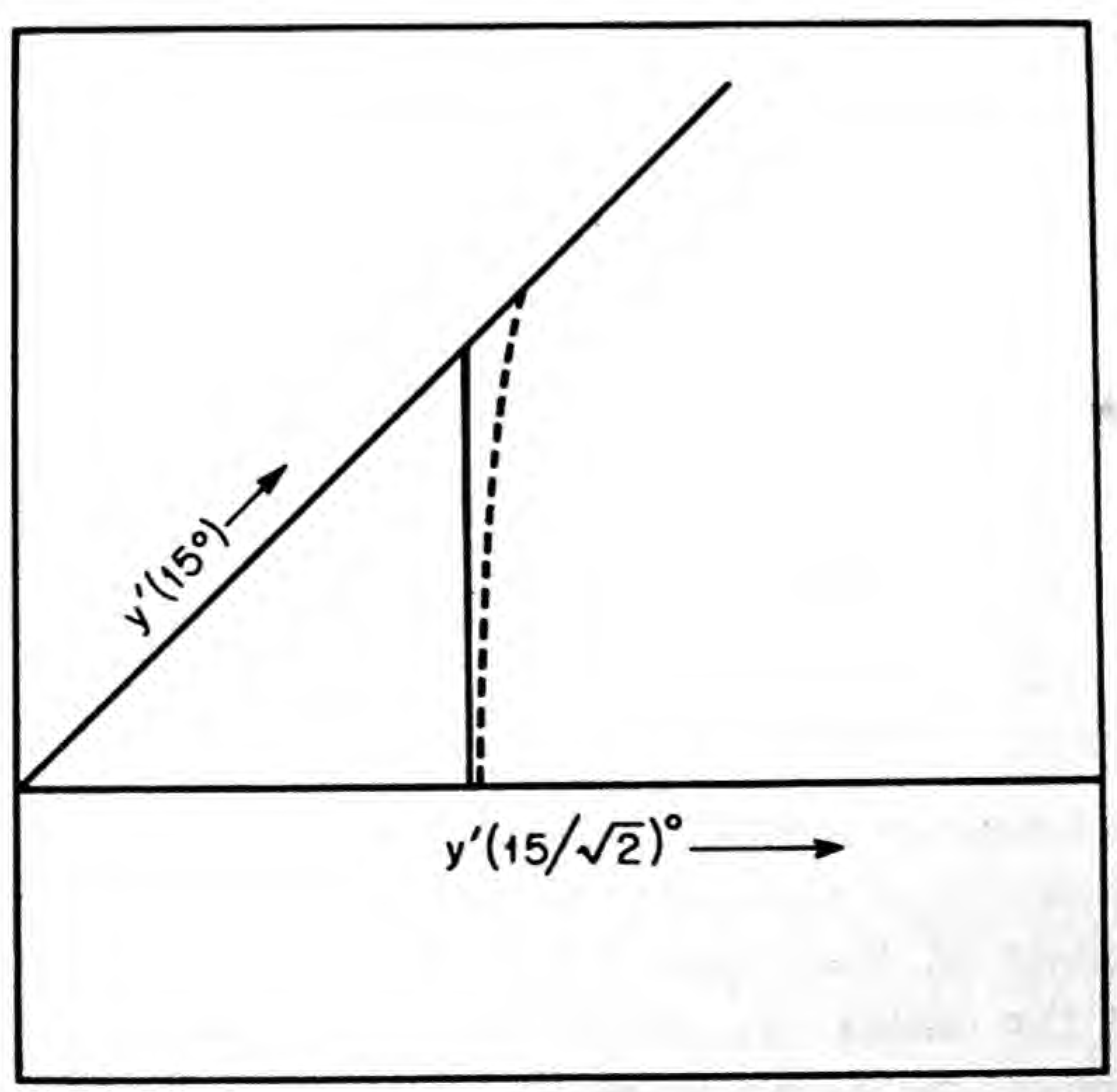


Fig. 9—Distortion of uncorrected plastic objective. ——, glass; -----, plastic.

Figure 11 shows $\Delta a'_F$ and $\Delta a'_C$ plotted against θ_9 and θ_5, respectively, from the original values obtained and from the values obtained from the color-correction formula. The points of intersection of the $\Delta a'_F$ and $\Delta a'_C$ curves for each parameter were found. These gave approximately the same values of $\Delta a'$. Although they corrected lon-

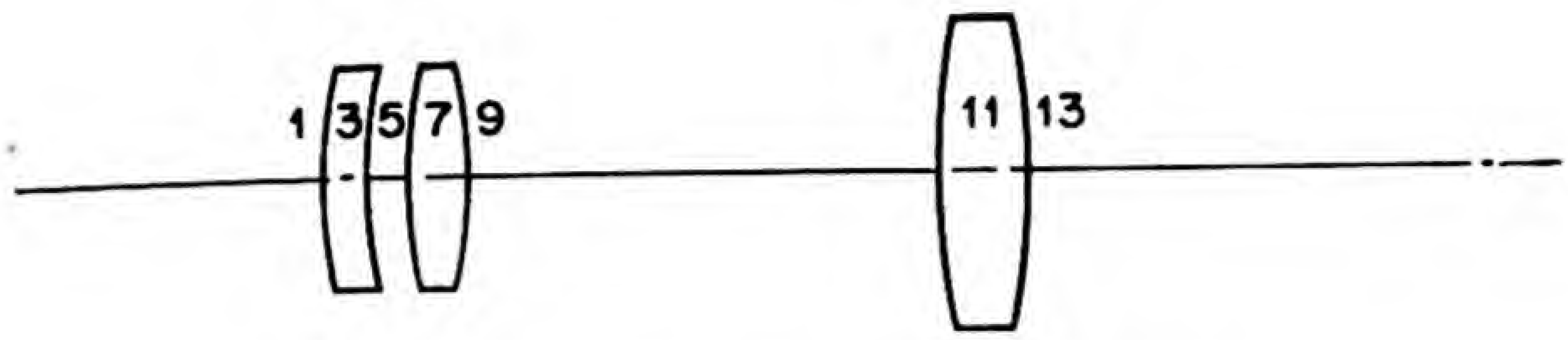


Fig. 10—Numbering system for media in lens system.

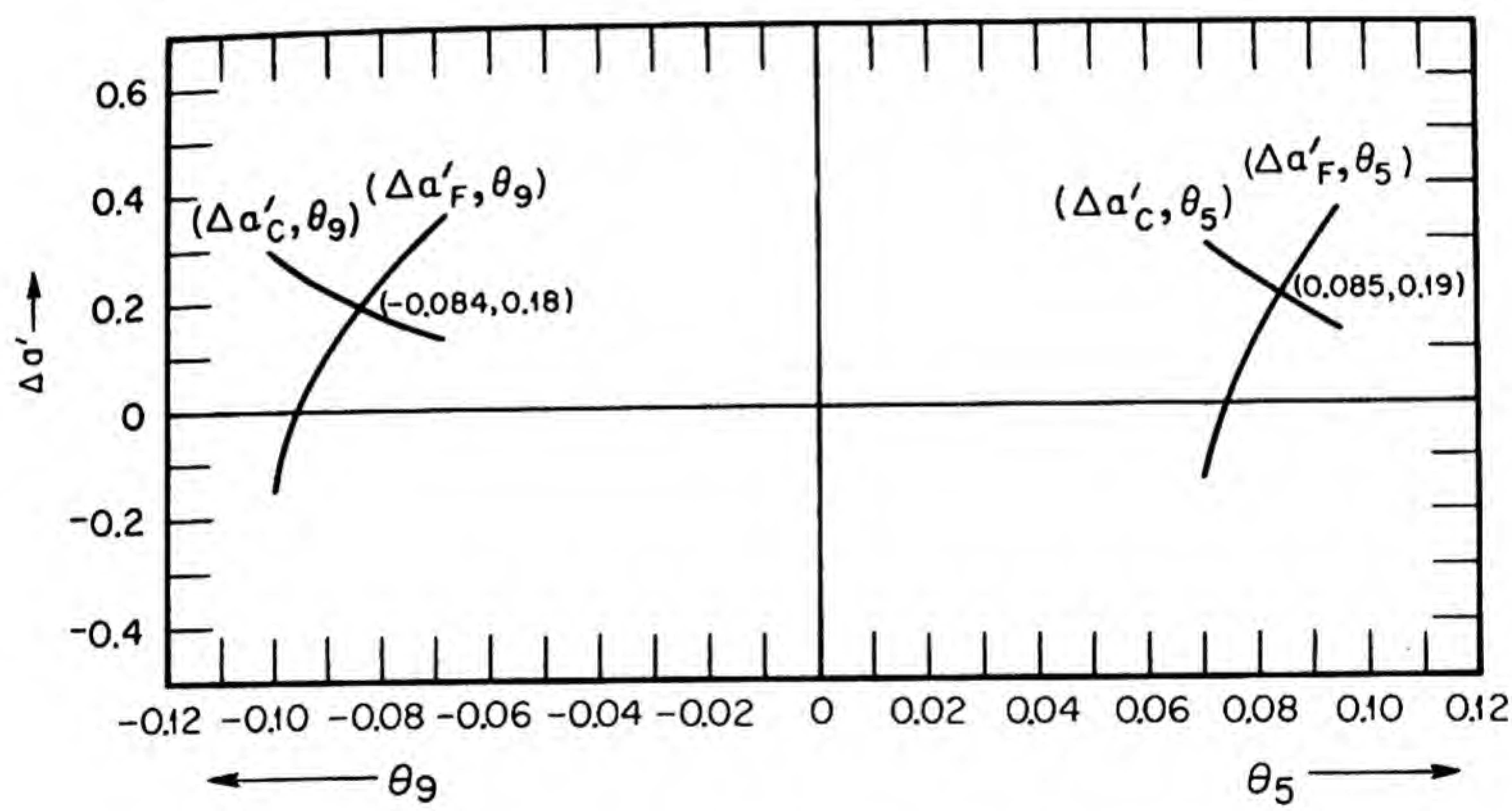


Fig. 11—Graph showing aberration of focal length before and after correction by the color-correction formula.

gitudinal color, these values could not be used because they caused radii of curvature smaller than the diameter of the opening. The only alternative was to give θ_5 the value shown to be the best from the graph. This would leave the doublet as well achromatized as possible. Then, if the field lens did not affect the image-forming rays, this correction would be adequate. To fix the field lens so that it would not affect these rays, the paraxial ray was made to cross the axis at the first principal plane of the field lens. Hence the power of the field lens could be changed without affecting the axial rays used in correcting for color.

Figure 12 is a drawing of the objective obtained after these changes were made. Its aberrations are given in Table 1.

Although the system is corrected as well as possible for longitudinal chromatic aberration, it is not so good as the glass system in this

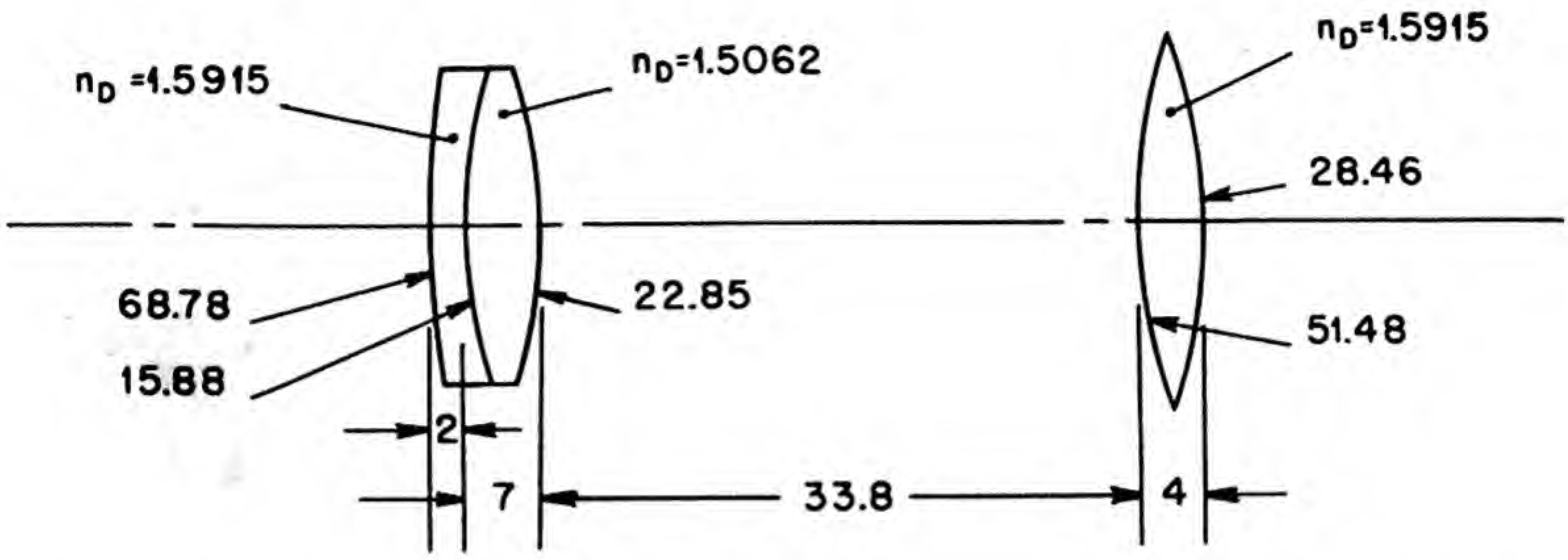


Fig. 12—Lens objective system after correction. Dimensions are in millimeters.

Table 1—Aberrations of Objective after Correction

	Plastic	Glass
Chromatic aberration		
Longitudinal type	See Fig. 3	
Lateral type		
Exact $\Delta y'$	0.0705	0.0972
Spherical aberration		
Longitudinal type	See Fig. 3	
Lateral type		
Exact $\Delta y'$	−0.0556	−0.0276
Coma		
Per cent	−0.0167	0.0089
Linear	−0.175	−0.110
Primary curvature of field		
x_P	−0.914	1.74
Distortion	See Fig. 13	

respect (see Fig. 13). The correction of color in plastics to the same degree as in glass will probably always be difficult with present-day plastics. There is very little difference in the Seidel aberrations of the Kollsman glass and the plastic objective. All calculations were made in order that the entrance-pupil position would be the same as that of the Kollsman objective (see Figs. 17 and 18).

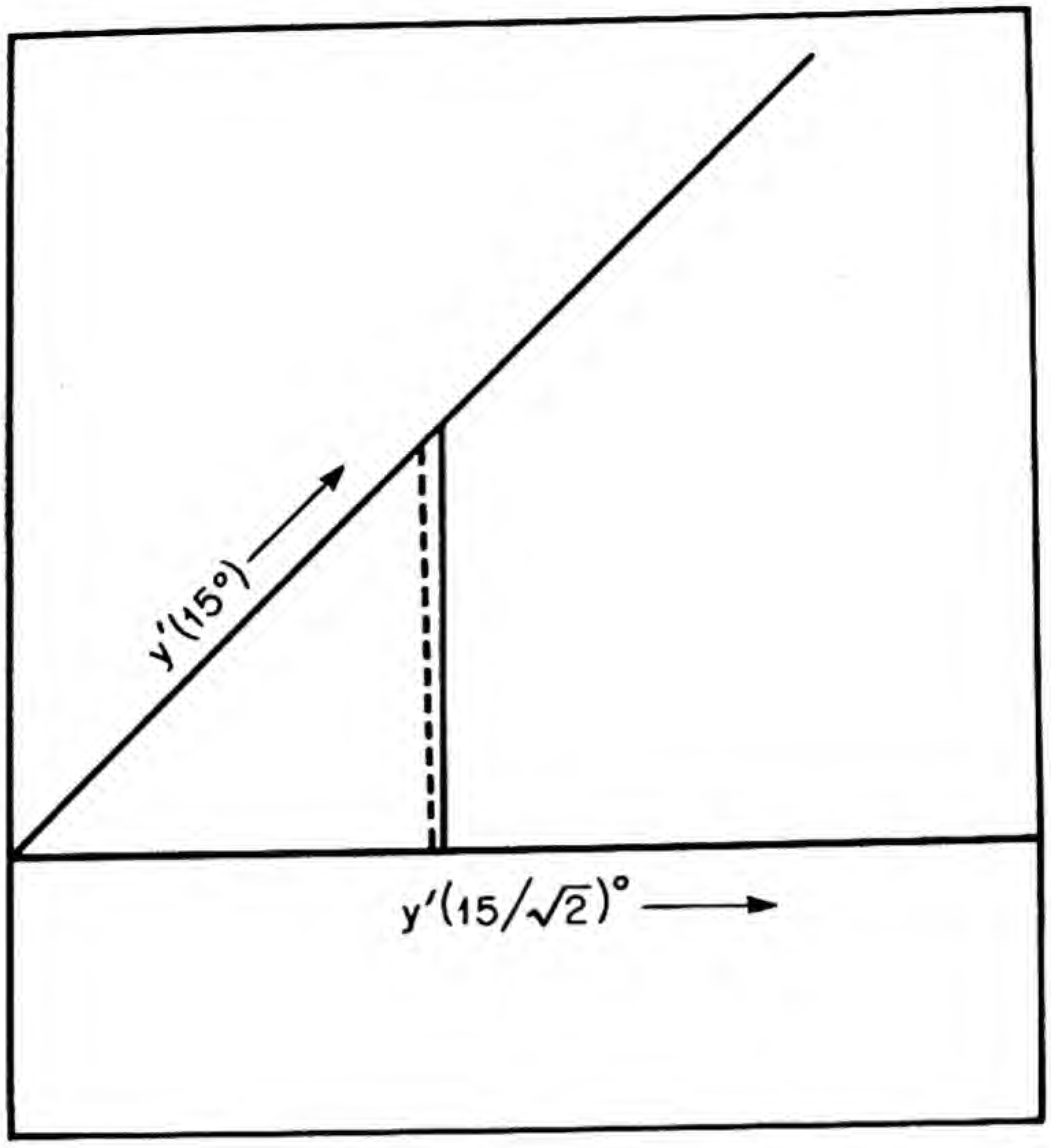


Fig. 13—Distortion of corrected plastic objective. ——, glass; -----, plastic.

3. REVISIONS OF SPECIFICATIONS

For simplicity in manufacturing, the field lens was changed from a meniscus to a plano-convex lens with the desired power. This power must be such that a chief ray crosses the axis at the exit pupil, in this case the first erecting lens, 241.9 mm from the field lens (see Fig. 14).

No noticeable change in aberrations will result since the position of the field lens was fixed so that it did not affect the image-forming rays.

After the preceding changes and calculations had been made, it was found necessary to have lenses with an edge thickness of at least 3 mm to prevent chipping and breaking while making them. The edge thickness was calculated by the approximate formula $\sigma = D^2/8r$, where σ is the dip, D is the diameter of the lens, and r is the radius of the surface. The data on this are given in Table 2.

The cyclohexyl methacrylate doublet lens edge thickness of 1.06 mm was too small. With the thickness equal to 9 mm instead of 7 mm, the convex lens of the doublet had an edge thickness of 3.11 mm. To prevent noticeable change in aberrations, θ's were left constant.

The objective had been designed for the first erector to be 241.9 mm away from the field lens. It was now decided to use the objective in a system where the first erector was 2 ft, or 609.6 mm, away. This change could easily be made since the field lens was so placed that changing its power had no effect on the image-forming rays. It

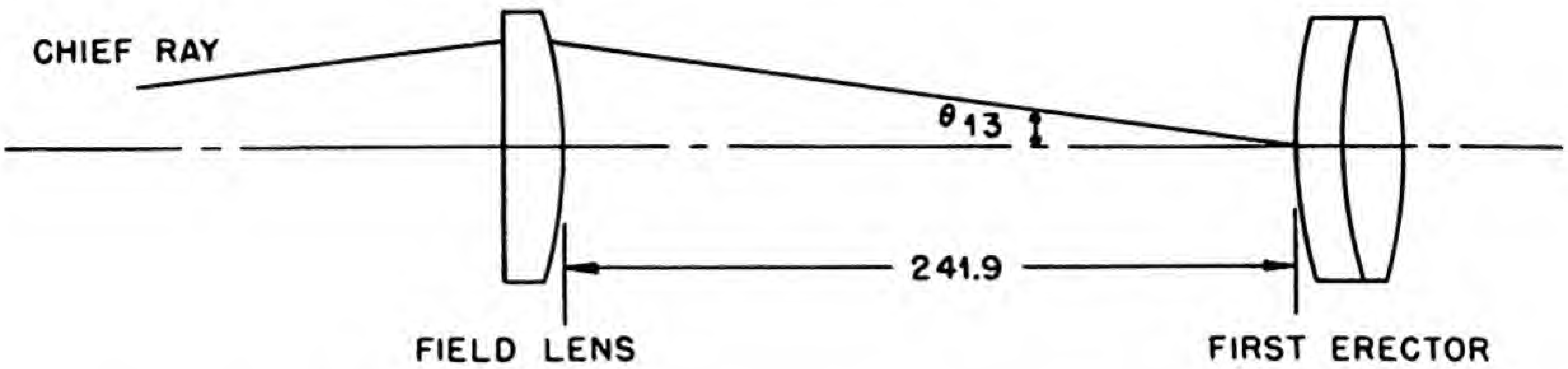


Fig. 14—Revised objective system with plano-convex field lens.

Table 2—Specifications for Lens Manufacture

Lens	Thickness, mm	σ	Edge thickness, mm
Styrene doublet	2	0.80	4.67
		3.47	
CHM doublet	7	3.47	1.06
		−2.41	
Styrene field lens	4	−0.22	3.78

was still made a plano-convex lens with a power such that the chief ray would focus at the exit pupil 609.6 mm away from the field lens.

It was then learned that previous reports on rate of discoloration of the plastics had been incorrect and that cyclohexyl methacrylate discolored at a slower rate than styrene. Changing the type of plastic in the field lens did not noticeably change the aberrations because the position of the field lens had been chosen so that it had no effect on image-forming rays. The design of the Kellner-type plastic objective can be found in Fig. 18.

The equivalent focal length of the Kellner-type plastic objective is approximately the same as that of the Kollsman objective. The former is 39.87 mm, and the latter is 40.13 mm. In all the designs of the plastic objective the entrance pupil has been kept the same as that of the Kollsman objective. Hence, in any instrument in which the Kollsman glass objective was intended to be used, this Kellner-type

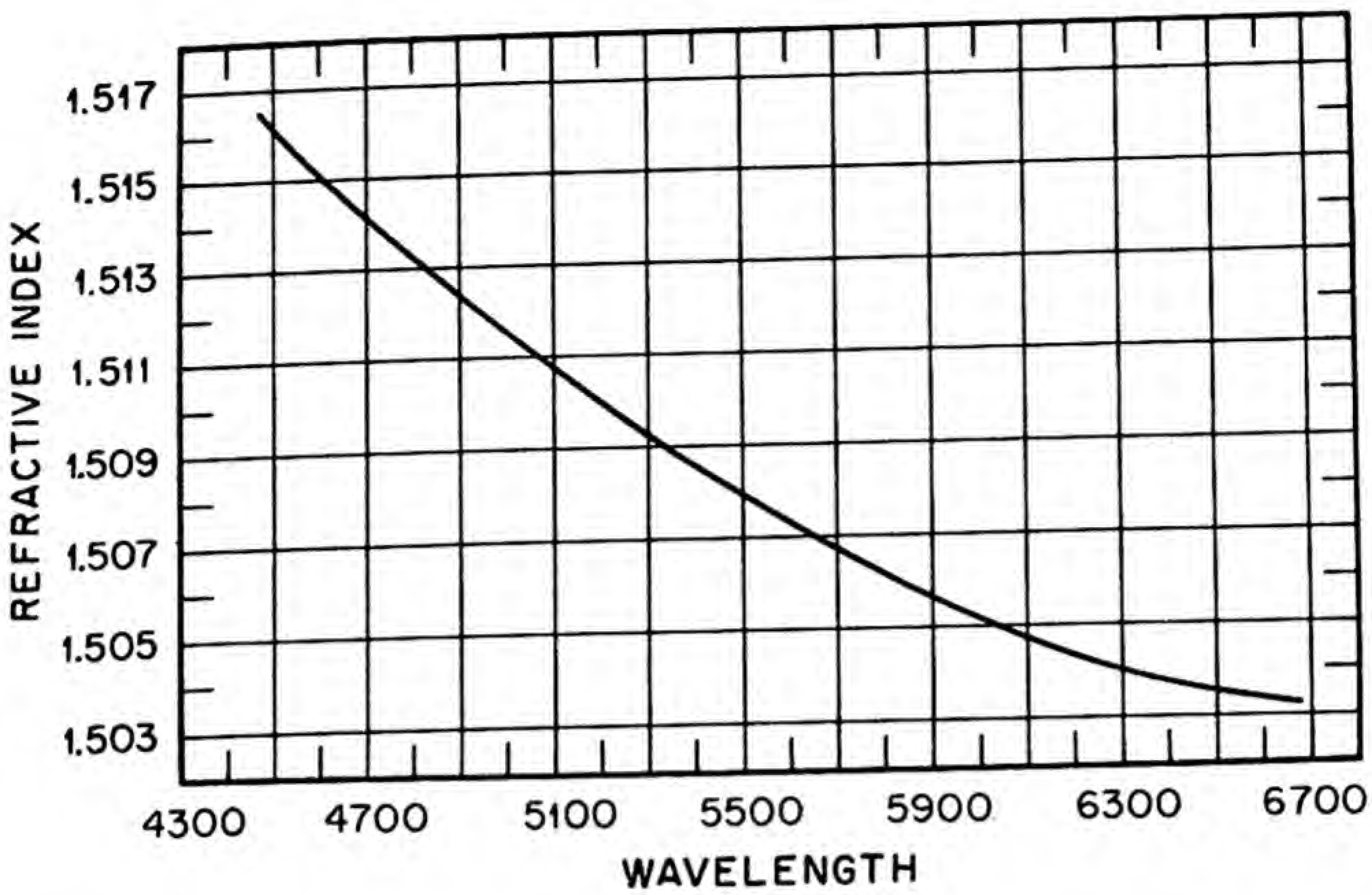


Fig. 15—Dispersion of cyclohexyl methacrylate (He source).

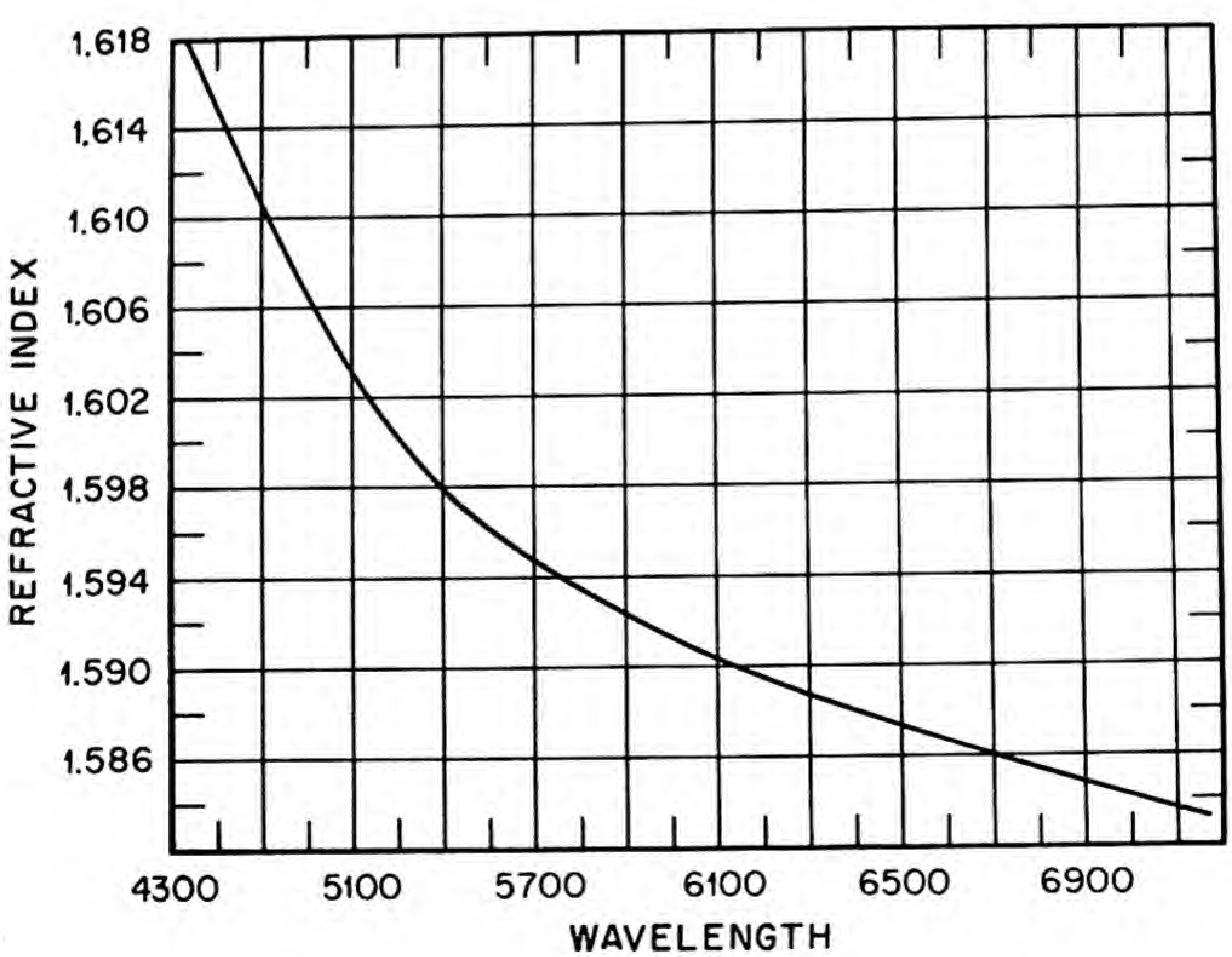


Fig. 16—Dispersion of styrene (He source).

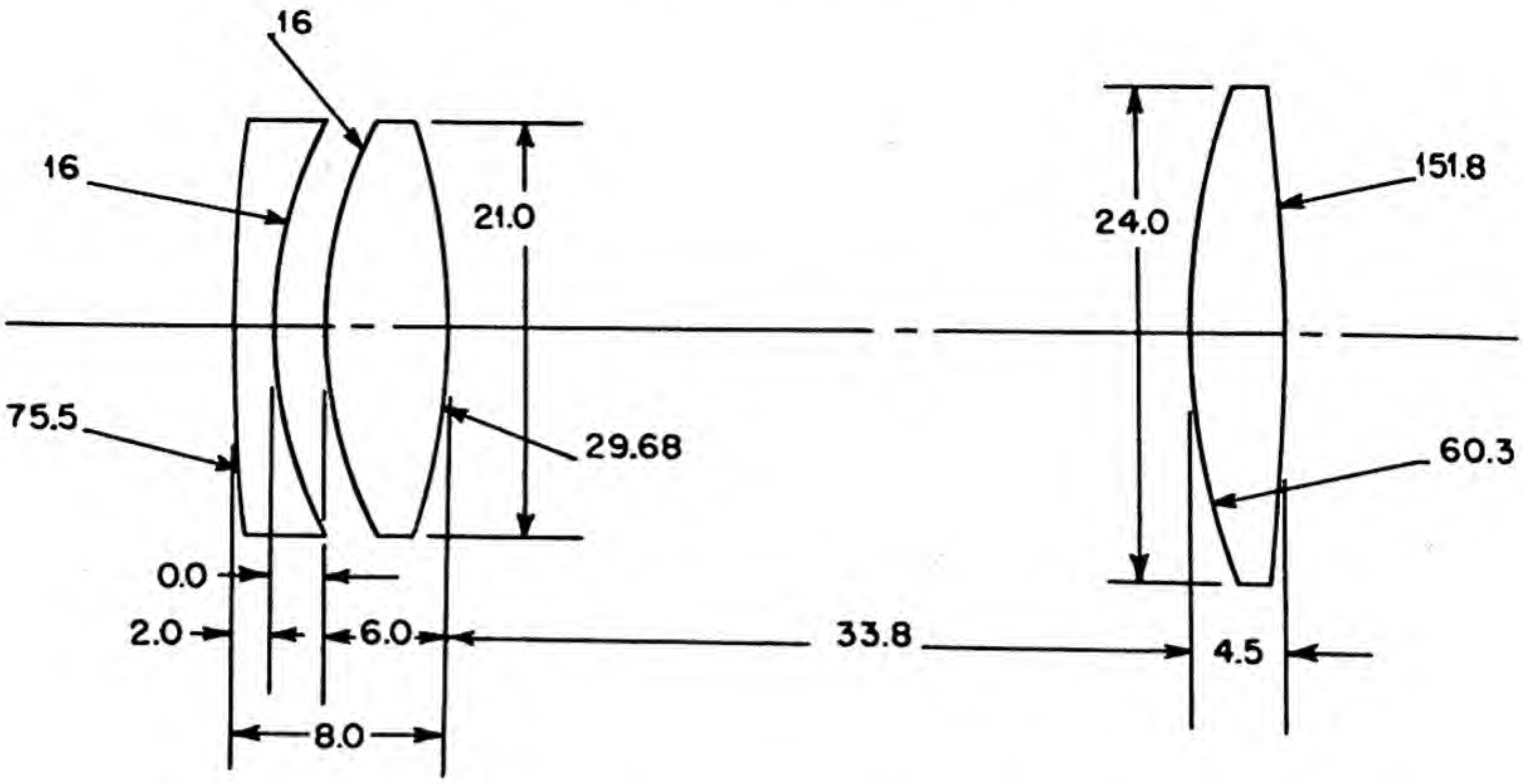


Fig. 17—Data for glass objective assembly (compare Fig. 18).

Diameter, mm	Material	Index
21.0	EDF-1	1.649
21.0	LBC-2	1.5725
24.0	BSC-2	1.515

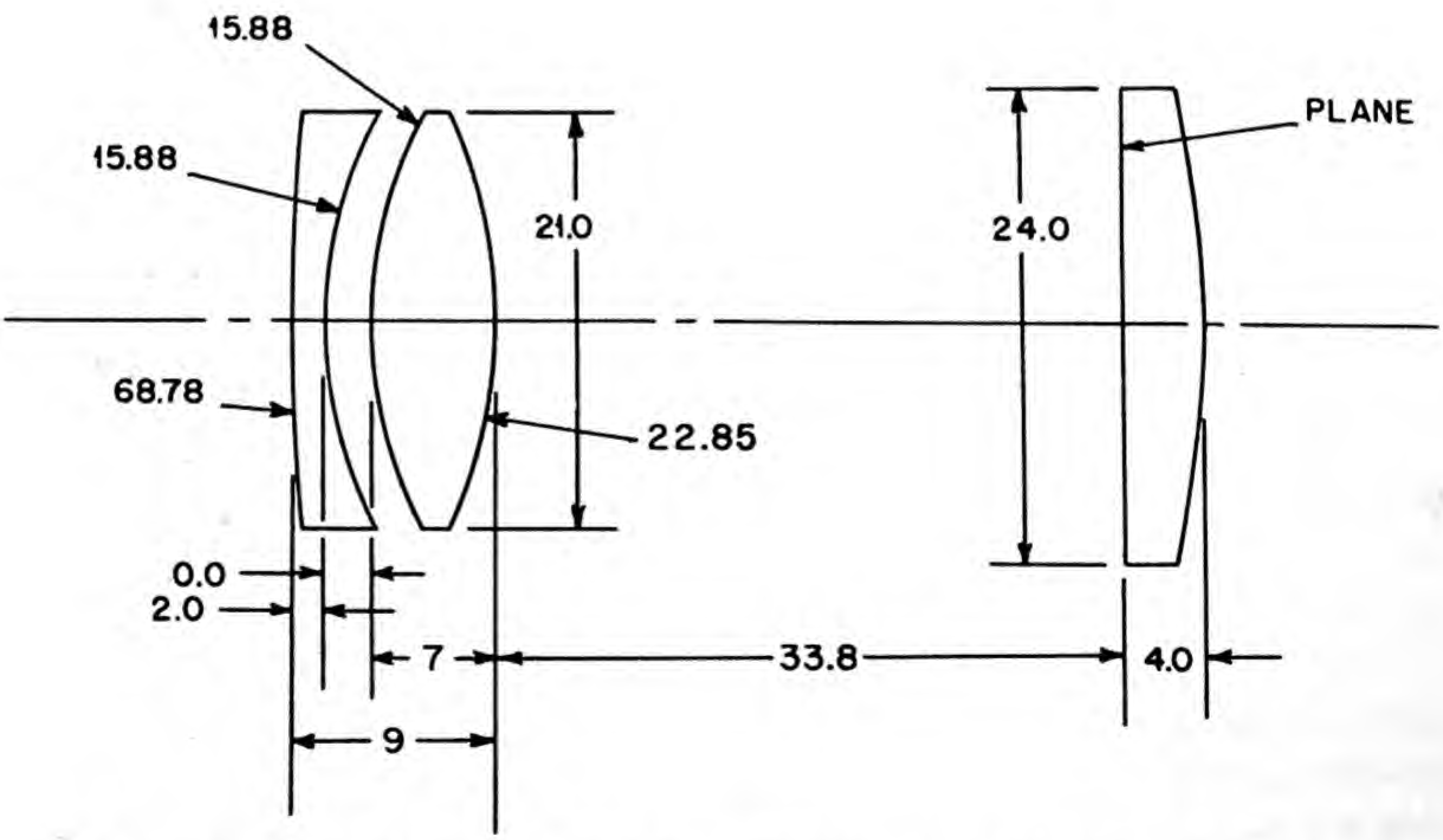


Fig. 18—Data for plastic objective assembly (compare Fig. 17).

Diameter, mm	Material	Index
21.0	Styrene	1.5915
21.0	CHM	1.5062
24.0	Styrene	1.5915

plastic objective can very satisfactorily replace it and give the same results.

Although the aberrations have not been determined for any of the revisions made, it is improbable that there will be any appreciable change in them because the parameters controlling these aberrations have been left unchanged.

Dispersion and design characteristics of the plastic objective assembly are shown graphically in Figs. 15 to 18.

APPENDIX

Luneberg's mathematical theory of geometric optics was used to trace rays through the lenses and to calculate the aberrations. In the nomenclature used, the odd subscripts denote media; the even subscripts denote surfaces; and a prime superscript relates to the image plane.

Exact Triangulation of a Ray. The following series of equations offers a solution to this problem.

$$\alpha_{i+1} = \alpha_{i-1} + \theta' - \theta$$

$$\theta = \sin^{-1} (\eta_i / n_{i-1} r_i)$$

$$\theta' = \sin^{-1} (\eta_i / n_{i+1} r_i)$$

$$\eta_{i+1} = \eta_{i-1} + n_i s_i \sin \alpha_i$$

$$a' = r_i - (\eta_i / n_{i+1} \sin \alpha_{i+1})$$

where n = index of refraction
r = radius of curvature
t = thickness of lens or distance between surfaces
α = slope angle of ray with optical axis
θ = slope angle of ray with radius of curvature
η = product of the index of refraction and the perpendicular distance P from the center of curvature to the rav
$s_i = t_i + r_{i+1} - r_{i-1}$ = distance between center of curvatures
a' = distance of image from any surface
i = *ith* medium

First-order Approximation. This approximation may be made in the following manner (see Fig. 19):

$$\theta_{i+1} = \theta_{i-1} - d_i h_i$$

$$h_{i+1} = h_{i-1} + \delta_i \theta_i$$

$$a' = h/\theta$$

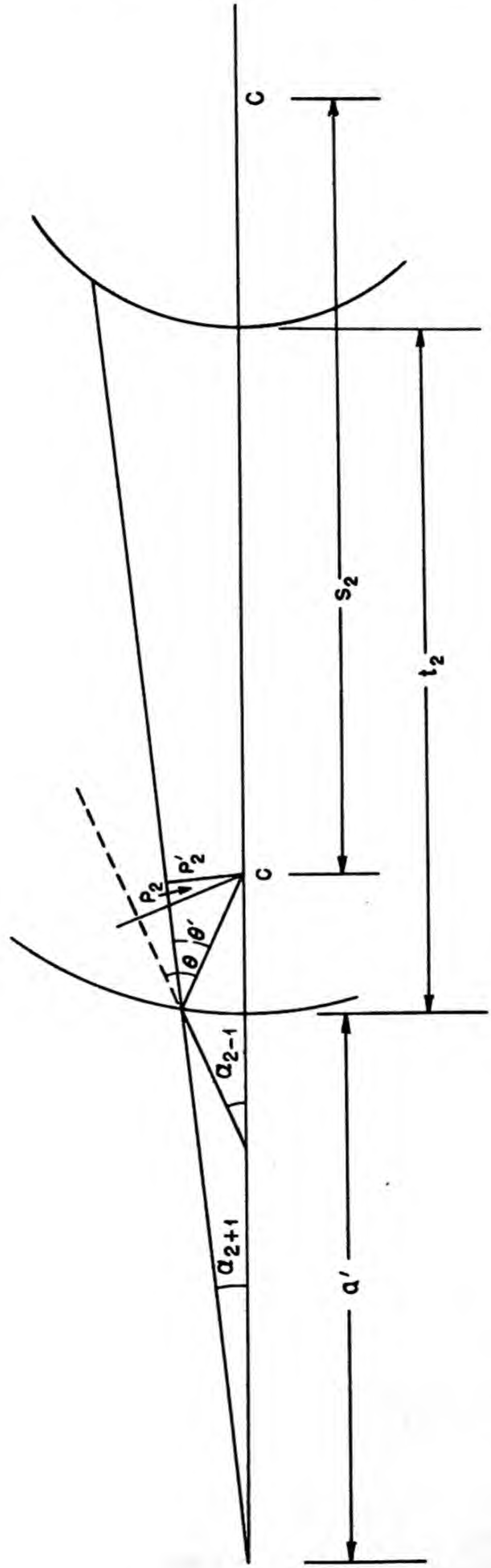


Fig. 19—Nomenclature for ray tracing illustrated.

where $\theta = n\alpha$, product of the index of refraction and the slope angle of the ray with the axis

h = height at which the ray strikes the surface

$d_i = (n_{i+1} - n_{i-1})/r_i$, power of the surface

$\delta = t/n$, product of the thickness of the lens and the reciprocal of the index

a' = image distance

In the special case of a chief ray, θ and h are used to denote the slope angle and height.

Aberrations. A third-order approximation of aberrations can be made using the first-order terms given above. The height of the ray in the image plane is given by

$$y' = My + A\alpha^3 + B\alpha^2 y + C\alpha y^2 + Ey^3$$

where M is the magnification.

The aberration coefficients are

$$A = -\left(\tfrac{1}{2}\theta_{\kappa+1}\right)\sum_{i=1}^{\kappa} S \qquad \text{lateral spherical}$$

$$B = -\left(\tfrac{1}{2}\theta_{\kappa+1}\right) 3\sum_{i=1}^{\kappa} S_i\omega_i \qquad \text{coma}$$

$$C = -\left(\tfrac{1}{2}\theta_{\kappa+1}\right)\left(3\sum_{i=1}^{\kappa} S_i\omega_i^2 - \Upsilon^2\sum \pi\right) \qquad \text{primary curvature}$$

$$E = -\left(\tfrac{1}{2}\theta_{\kappa+1}\right)\left(\sum S_i\omega_i^3 - \Upsilon^2\sum \pi_i\,\omega_i\right) \qquad \text{distortion}$$

where $\pi_i = d_i/(n_{i-1}n_{i+1})$

$$\omega_i = \frac{\Delta_i(\theta/n)}{\Delta_i(\theta/n)}$$

$$\Upsilon = H_0\theta_1$$

denote the last medium.

First-order approximation of chromatic aberration is given by

$$K = (1/\theta_{\kappa+1})\sum_{i=1}^{\kappa} T_i$$

$$\Delta a' = -K/\theta_{\kappa+1}$$

$$\text{where } T_i = \frac{\Delta_i(m/n)}{\Delta_i(1/n)\; h_i\Delta_i(\theta/n)}$$

Paper 1.5

ACHROMAT WITH POSITIVE ELEMENT OF TWO PLASTIC FIELD LENSES*

By Minnie Mrjenovich

ABSTRACT

In this report is given the design for a styrene-plastic negative element to form an achromatic lens when combined with two uncemented plastic C-field lenses, a number of which were in stock. Molds were not on hand for the negative element designed, but the available molds could be used to form a negative plastic element which would produce a reasonably satisfactory achromat when combined with two cyclohexyl methacrylate C-field lenses.

1. INTRODUCTION

The achromat considered in this paper was designed with utilization of the excess C-field lenses on hand. These plano-convex C-field lenses were made of cyclohexyl methacrylate ($n_D = 1.5062$), and the focal length was 304.8 mm. A 12-in.-focal-length doublet using the C-field lens as one element could not be achromatized very well, and therefore a triplet was designed. One method suggested in designing this triplet was to place the plane surfaces of two C-field lenses together and to choose the third element, either plastic or glass, of an index that would make the triplet as well achromatized as possible. Thus the achromat would be treated as a doublet with a double-convex first element rather than a triplet.

*This paper is based on Report CP-3084, June 30, 1945.

2. PROPOSED ACHROMAT

The third element that was considered at first was of styrene (n_D = 1.5915), with the radii and thicknesses shown in Fig. 1. In Fig. 1, the equivalent focal length is 304.8 mm, or 12 in.; the back focal length is 296.58 mm, or 11.68 in.; and the radius R is −1078.44 mm.

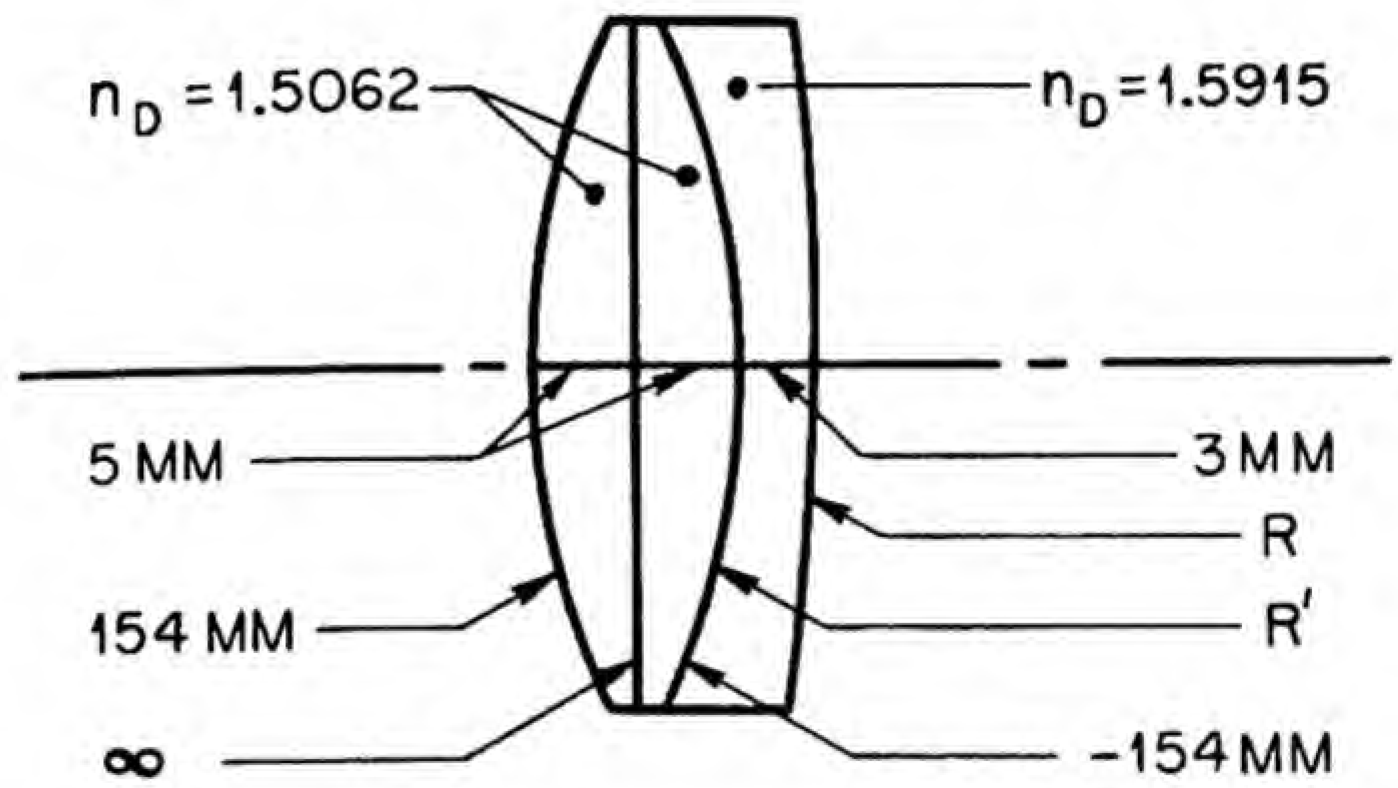


Fig. 1—Achromatic lens of two plano-convex cyclohexyl methacrylate elements and one styrene element. Diameter, 33.88 mm, or 1.334 in.; clear aperture, 33 mm, or 1.299 in.

3. REVISED RADII OF NEGATIVE ELEMENT

Since the Polaroid Corp. did not have a convex mold of 154 mm or a concave mold of 1078.4 mm, the radii of the negative element of the achromat were changed to those of available molds. The convex molds closest to 154 mm are 128.6 and 160.32 mm. The concave molds closest to 1078.4 mm are 836.4 and 1130.6 mm. Spherical and chromatic aberrations were calculated for the four different achromats obtained by using all combinations of the above radii for the negative element. These aberrations are listed in Table 1.

Spherical and chromatic aberrations are very bad for cases 1 and 2, that is, where the first radius of the negative element is −128.06 mm. With the first radius equal to −160.32 mm, as in cases 3 and 4, there is very little difference in spherical and chromatic aberrations when the last radius is changed. Spherical aberration is slightly smaller in case 4; therefore it was taken as the negative element. For case 4 (see Fig. 1) the equivalent focal length is 293.92 mm, or 11.572 in.; the back focal length is 285.90 mm, or 11.256 in.; the radius R is −1130.6 mm, or 44.513 in.; and the radius R′ is −160.32 mm, or 6.312 in.

Table 1 — Spherical and Chromatic Aberrations of Achromats

Case	Radii of negative element, mm	Spherical third-order $\Delta a'$	Chromatic $\Delta a'_F$	First-order $\Delta a'_C$
1	−128.06 −836.17	4.02	3.71	1.41
2	−128.06 −1130.6	4.80	5.02	1.41
3	−160.32 −836.17	−1.17	0.21	1.30
4	−160.32 −1130.6	−0.98	0.66	1.30

Table 2 — Aberrations of Original Achromat and of Achromat with Revised Radii*

Aberrations	Original achromat	Achromat with revised radii
Chromatic †		
Longitudinal		
$\Delta a'_F$ (first order)	1.01	0.66
$\Delta a'_F$ (exact)	−0.4	−1.0
$\Delta a'_C$ (first order)	1.34	1.32
$\Delta a'_C$ (exact)	−0.4	−0.2
Lateral		
$\Delta y'$	0.028	−0.0082
Coma		
B	0.033	0.0160
Spherical†		
Longitudinal		
$\Delta a'$ (third order)	−0.48	−0.98
$\Delta a'$ (exact)	−0.3	−0.8
Lateral		
$\Delta y'$	−0.053	−0.055
Primary curvature,		
C	−0.088	−0.089
X	−1.63	1.54
Distortion		
E	0.00045	−0.00042

*For diagrams and detailed explanation, refer to Paper 1.4.

†See Figs. 2 and 3.

4. COMPARISON OF ACHROMAT OF REVISED RADII WITH ORIGINAL ACHROMAT

Table 2 gives the aberrations calculated for an achromat having the original proposed dimensions and for an achromat having the revised dimensions, as in case 4.

It can be seen from Fig. 2 that the original lens is as well achromatized as possible since the exact F, C, and D lenses are almost at

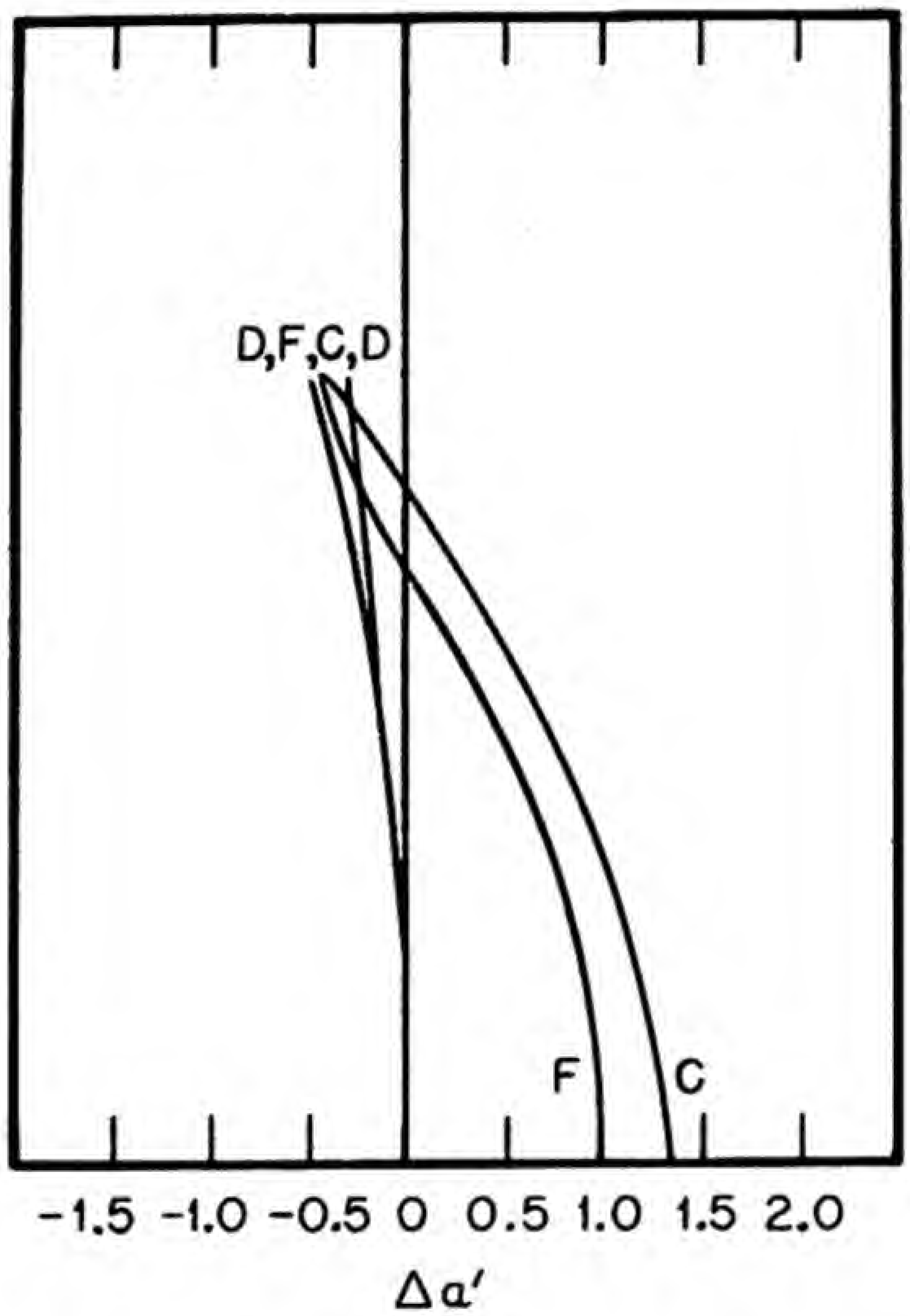


Fig. 2—Chromatic and spherical aberration (longitudinal) of achromat with original proposed dimensions.

the same point and the first-order F and C lenses are closer to the D line, since, by the theory of chromatic aberration, the change in $\Delta a'_F$ is about three times greater than the change in $\Delta a'_C$.

If Fig. 3, which is a graph of the chromatic and spherical aberrations of the achromat with the revised radii, is compared with Fig. 2, it can be seen that the longitudinal first-order C line is approximately the same, whereas the F line is closer to the vertical axis. It is desirable to have the F and C lines closer together, but this new separation is not too serious. The exact longitudinal color, which is more important than the first order, has the F and D lines together but

further away from the axis, whereas the C line is closer to the axis. The ideal case for a lens to be well achromatized would have the F, C, and D lines as close together as they are in Fig. 2; however, the separation in Fig. 3 is not great enough to be serious. Spherical

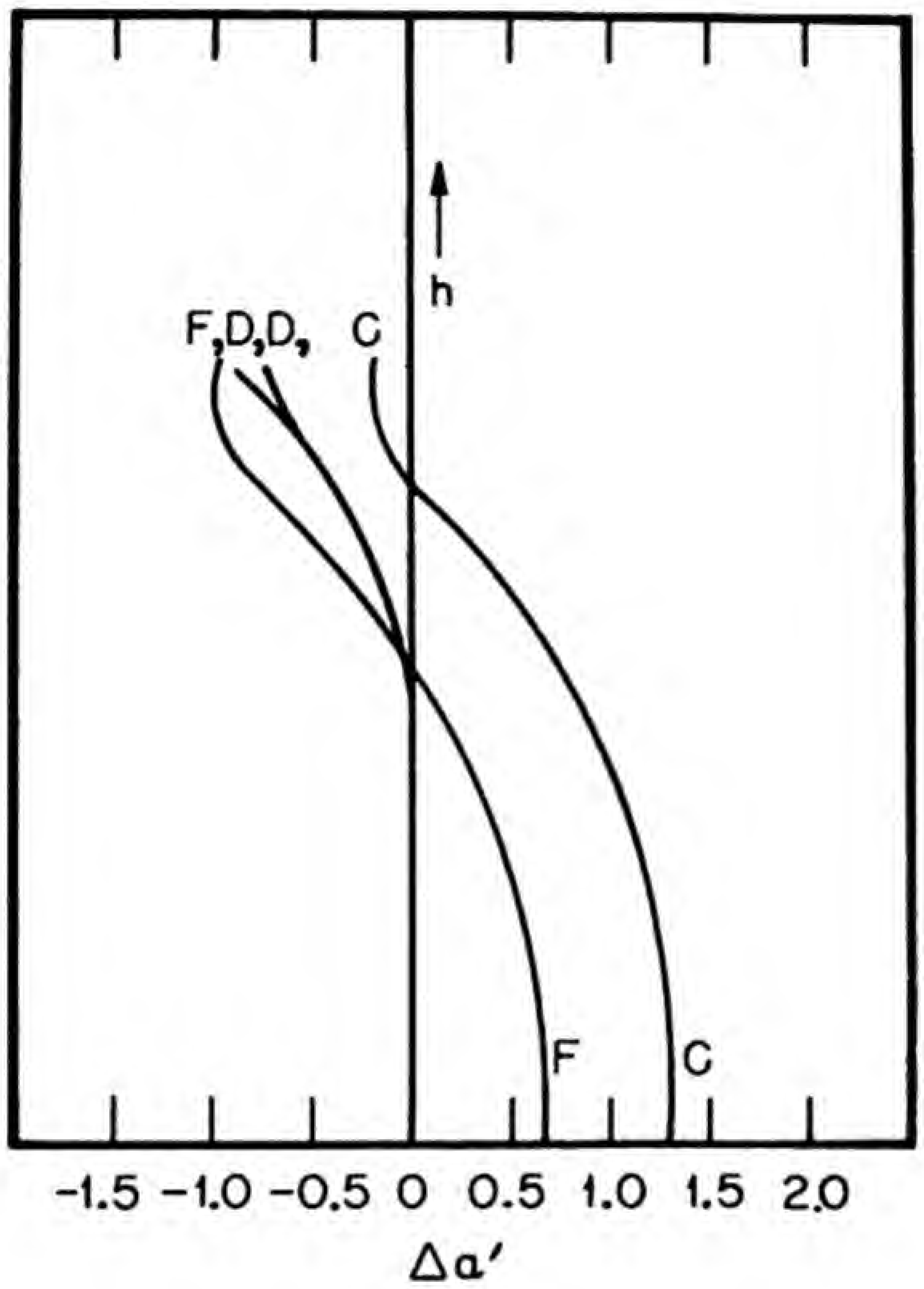


Fig. 3—Chromatic and spherical aberration (longitudinal) of achromat with revised radii.

aberration is a little worse for the achromat with the revised radii, but again it is not serious. Coma and primary curvature are slightly less, and distortion is still very small, but it is of a different sign which makes it barrel distortion.

Paper 2.1

BORESCOPES IN THE PROJECT*

By George S. Monk, W. H. McCorkle, Minnie Mrjenovich, and Elaine Sammel Palevsky

ABSTRACT

A comparison of two types of borescopes constructed for Project use is made, and a detailed description of the construction and operation of the borescope developed for use in water-filled Hanford-type tubes is given in this paper. Values of the aberrations of the erector lenses are tabulated, and results of studies on a circumference-viewing head are also given.

1. THE FIRST BORESCOPE

A borescope is simply a long narrow periscope (see Paper 1.1) designed for the special purpose of inspecting the inside of tubes, gun barrels, and steam lines. The possible variations in optical and mechanical design depend on the conditions of use.

The first borescope constructed for the Project was designed for use in an area where there was plenty of space in front of the tubes to be inspected. Therefore the entire instrument could be assembled into a single unit, and its full length could be pushed continuously into a tube. For this reason a design was adopted in which the lenses have a focal length of about 30¼ in., and the tube sections are 10 ft long. The system, as shown in Fig. 1, begins with an objective assembly O, consisting of a short-focus objective and a field lens. The image I, thus formed, is close to the surface of the field lens, and rays pass thence to a well-corrected achromat L_1 of focal length equal to half

*This paper is based on Reports CP-2325, Feb. 10, 1945, and CP-3077, June 26, 1945.

the distance from I_1 to L_1. Hence an image I_2 of equal size is formed beyond L_1 at the same distance as I_1 is from L_1. At this position, a second field lens F_1 of the same focal length as L_1 serves to bend the rays back toward the axis. Since F_1 is practically at the image position, it contributes very little to the image-forming functions of the lens system, and it can be merely a simple lens. Beyond this point the system of two lenses, L_1 and F_1, is repeated as many times as required to carry the image to the end of the tube or bore.

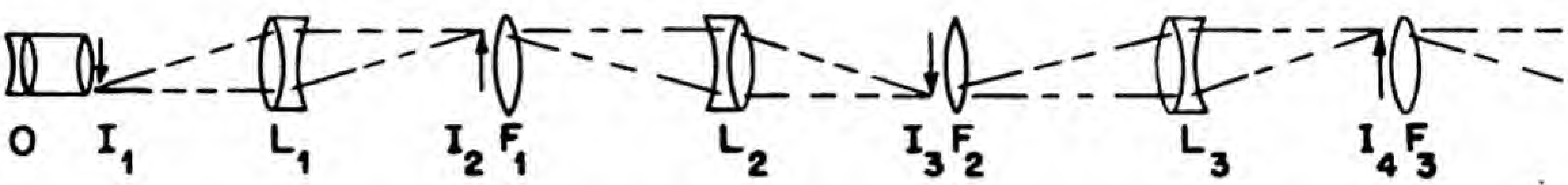


Fig. 1—First borescope design.

An obvious characteristic of this system is that it can furnish a large field because of the introduction of the field lenses. A limitation is its inflexibility in length. Although it is possible to change the separations of the lenses L_1, L_2, etc., any such change will always increase the distance between images and change the magnification. Also, it is more than likely that the field lenses will then be so far from the image positions that they will take on image-forming functions which will be detrimental to the final image.

When the first borescope was being planned, little was known of the amount of radiation present and its effects on the glass parts (see Paper 3.2). It was believed that plastic lenses could be made which would have greater resistance to radiation, but at the time these were not procurable in quantity. However, if the glass parts become colored, they may now be replaced by plastic parts.

This borescope, which may be used to inspect a dry tube about 32 ft long, has for a carriage a V-shaped groove and is moved manually in and out of the hole. The part of the instrument inserted into a tube has an outside diameter of 1⅜ in.

2. REQUIREMENTS FOR THE SECOND BORESCOPE

To view the inside of a tube, the second borescope (Fig. 2), a standard design consisting of an erecting system, focusing lenses, and a Kellner eyepiece, is to be fed from a space 8 ft wide into the tube to be inspected. This means that the instrument is assembled in sections as it is pushed into the tube and disassembled as it is drawn out.

An erecting system which repeats every 8 ft is required, and, for greatest convenience, sections of the instrument are interchangeable.

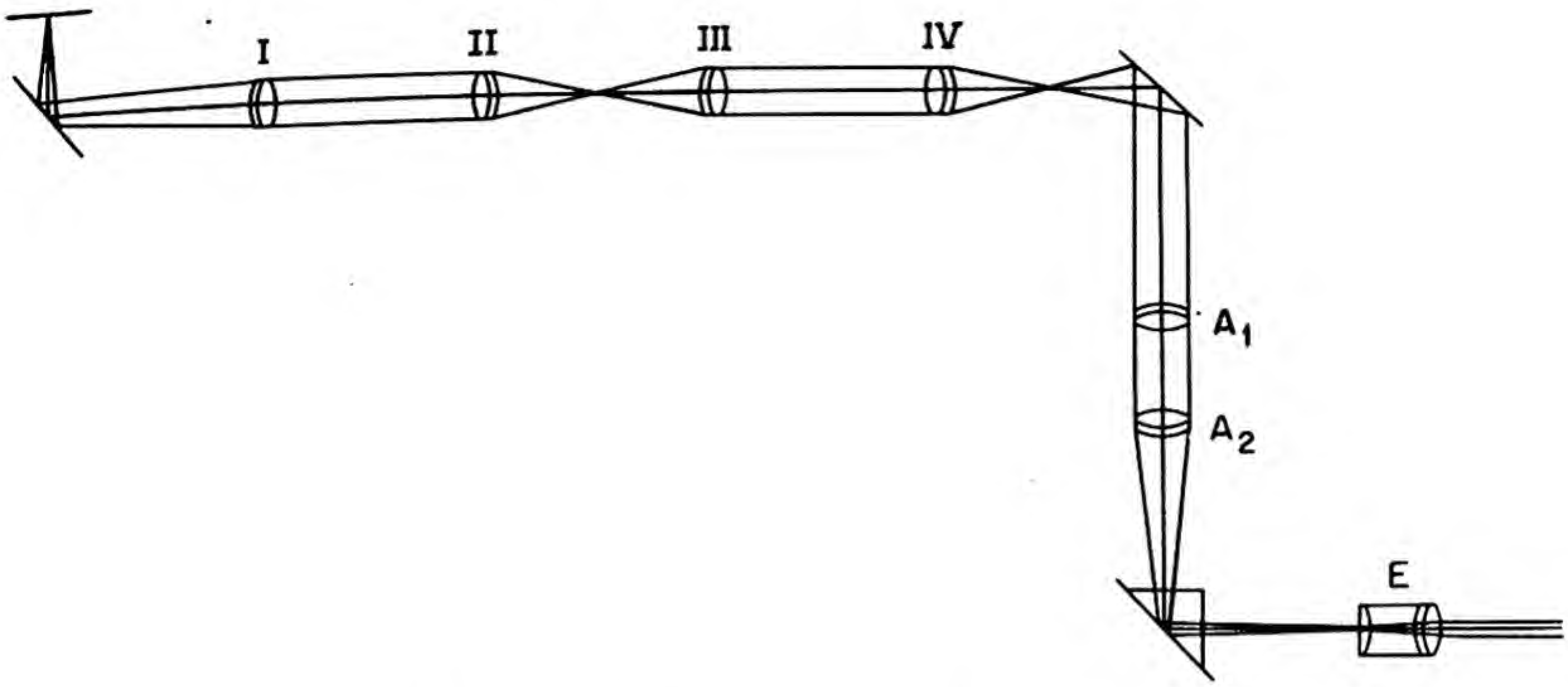


Fig. 2—Second borescope design.

3. ERECTING SYSTEM

The system used is shown in Fig. 3. The objective element is the same as in the first borescope, but the distance I_1L_1 is equal to the focal length of L_1, and therefore the rays from a given object point

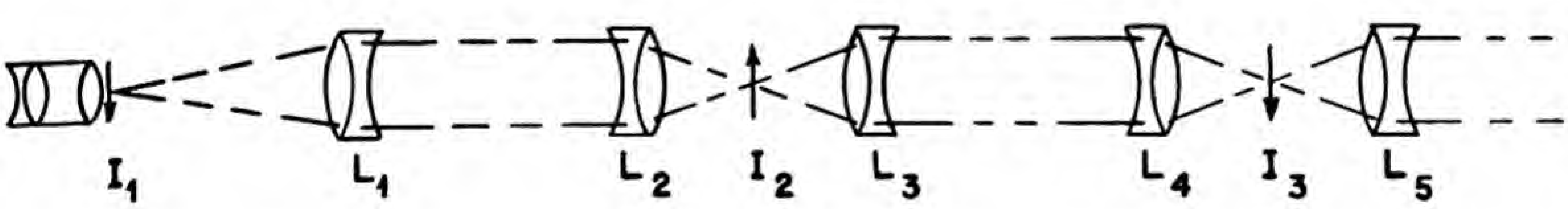


Fig. 3—Erecting system.

are parallel beyond L_1. A second achromat L_2 forms an image I_2, and, from then on, the system between I_1 and I_2 is repeated as many times as necessary to carry the image down the tube. Since the rays between L_1 and L_2 are parallel, unlike the first borescope, the distance between them can be varied to suit mechanical requirements without affecting the clarity of the image.

3.1 Lens Material. Two plastics, cyclohexyl methacrylate and polystyrene, have been developed by the Polaroid Corp. to the point

that they are entirely adequate for use near nuclear radiation. No serious coloration results when these plastics are used (see Table 1).

Table 1 — Relative Effect of Radiation on Polystyrene and Cyclohexyl Methacrylate Plastics

Plastic	n_D	ν	Exposure, r	Effect
CHM	1.5062	56.6	10^6	Slightly yellow
Polystyrene	1.5912	29.1	10^6	Unaffected

Table 2 — Comparison of the Aberrations of the Lenses for Cases 1 and 2*

Aberrations	Case 1	Case 2
Spherical (longitudinal)		
$\Delta a'$ (third-order)	−1.75	−1.75
$\Delta a'$ (exact)	−1.3	−1.51
Coma		
B	−0.005373	+0.003075
Curvature		
C (primary)	−0.08652	+0.08684
X_P	−0.00680	+0.006801
Distortion	+0.001103	−0.0004397

* For diagrams and detailed explanation, see Paper 1.4.

3.2 Aberrations. The lenses are 12-in.-focal-length doublets of cyclohexyl methacrylate and polystyrene. In using a train of identical lenses, improper facing will cause addition of the residual aberrations, whereas proper facing may bring about cancellations of these aberrations. Table 2 indicates the results of calculations made to determine the aberrations of the lenses for a ray entering the cyclohexyl methacrylate element first (case 1) and for a similar ray entering the polystyrene element first (case 2).

3.3 Light Transmission. The other consideration in the proper placement of the erecting lenses is the factor of the maximum distance between lenses which enclose parallel rays for the maximum light transmission. In order to calculate this distance, the bundle of rays coming from the point on the object farthest from the axis must be considered.

If one-half of a bundle of rays coming from a point on an object is cut out, the eye can detect no loss of light, but, if more than one-half of these rays is lost, the eye will notice a decrease in brightness. If the chief ray which passes through the center of the entrance pupil can traverse a whole optical system without destruction, then at least one-half of the bundle from a given point will traverse the entire system. In this case, if a chief ray from the highest point on the object reaches the second erector, the image will have the maximum amount of brightness.

For a ⅞-in. field the first erector should not be more than 438 mm from the objective for maximum brightness. The maximum allowable distance between erectors, after the first, is 1980 mm. The distance 2f = 609.6 mm between lenses is thus small enough to ensure maximum brightness of the image.

4. CROSSARM

It is not necessary to use plastic optical parts in the crossarm of the borescope because this section of the instrument is sufficiently

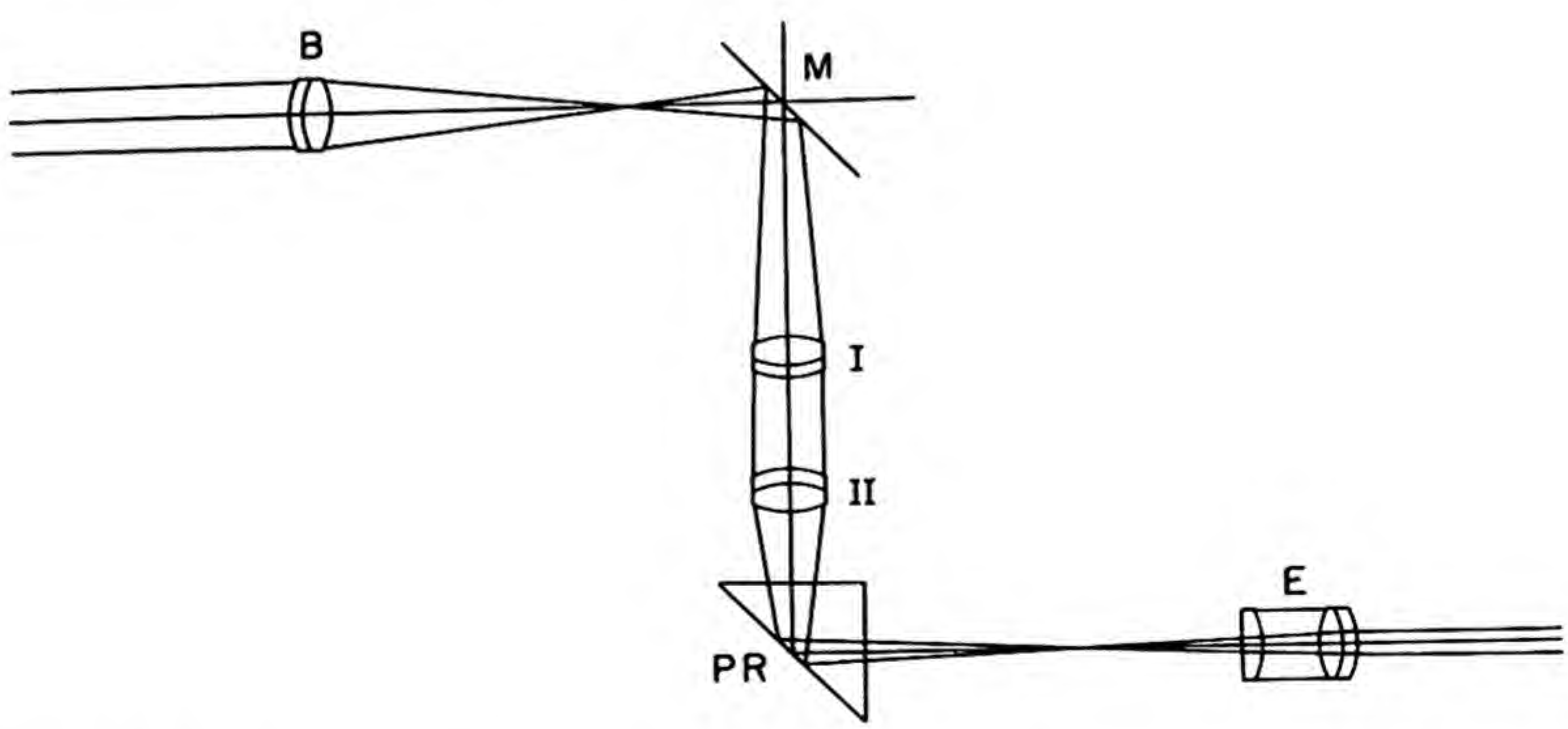


Fig. 4—Lens system showing use of mirror and prism to bend light rays.

shielded from radiation. Glass lenses of 24 and 22 in. focal length are used as the adjusting lenses. A front-surface-aluminized mirror, set at 45 deg to the axis of the borescope sections, and a 90-deg prism are used to bend the light rays around the corner (see Fig. 4).

The tube to be viewed contains internal ribs. The image formed by a point on the rib will occur at a different position in the lens sys-

tem from that formed by a point on the inner circumference of the tube. A focusing lens may be adjusted, by means of a focusing nut, to permit a view of a rib, the circumference, or any point in-between.

5. EYEPIECE

Final adjustment of the focus is made by movement of the eyepiece. The Kellner-type eyepiece was designed and manufactured for use with a periscope. It has a magnification of about 2. An image formed 5 mm from the field lens of the system forms parallel rays.

6. HEAD

Since the plastic objective assembly is inferior to a corresponding glass system, the ordinary objective is omitted in this instrument.

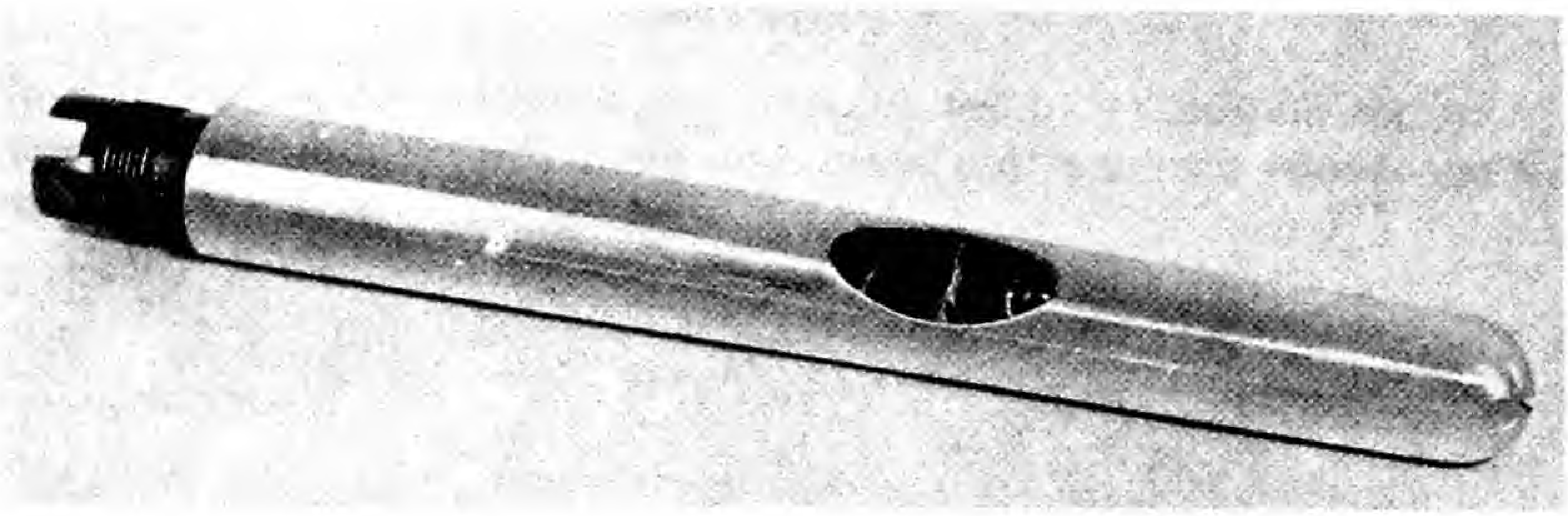


Fig. 5—Borescope head.

This omission is possible because magnification of the objective is approximately unity, and the limitations on lens size imposed by the need for water-sealing around the objective mean that the field lens did nothing to enhance field size.

6.1 Right-angle Viewing Head. The borescope head (Fig. 5) consists of a bullet-shaped stainless-steel cap screwed on the end of an 8-in. length of lead-filled stainless-steel tubing $1\frac{3}{8}$ in. in outside diameter. A length of stainless-steel tubing having an elliptical opening in its side, a slotted bronze connecting device soldered into one end, and an outside diameter of $1\frac{3}{8}$ in. is screwed to the lead-filled portion. Inside the tubing with the elliptical opening is located a 21-cp 6-volt lamp and a mirror set at 45 deg to the axis of the tubing and arranged so that the side of a water-filled ribbed aluminum tube may be illuminated. Light from the illuminated portion is reflected down

the borescope to succeeding sections of the instrument. Mounted in the bronze connecting device between the head and succeeding sections is a flat plastic dish or window about 1 in. in diameter, sealed by rubber gaskets so that water can be kept out of the borescope sections.

6.2 Circumference Head. Since the borescope is designed to be used with a rotating mirror which enables the observer to see small portions of the tube at a time, a field of little depth is produced so that the borescope may be used for a close-up view of any particular portion of the tube. By combining finished lenses of known design, it has been found experimentally that an achromat (see Paper 1.5) of 37.1 mm focal length placed 30.2 mm from a field lens of 304.8 mm focal length forms an objective with a field of great depth which, when used in conjunction with the borescope train of lenses, is limited only by the observer's eyes and the illumination of the tube. This objec-

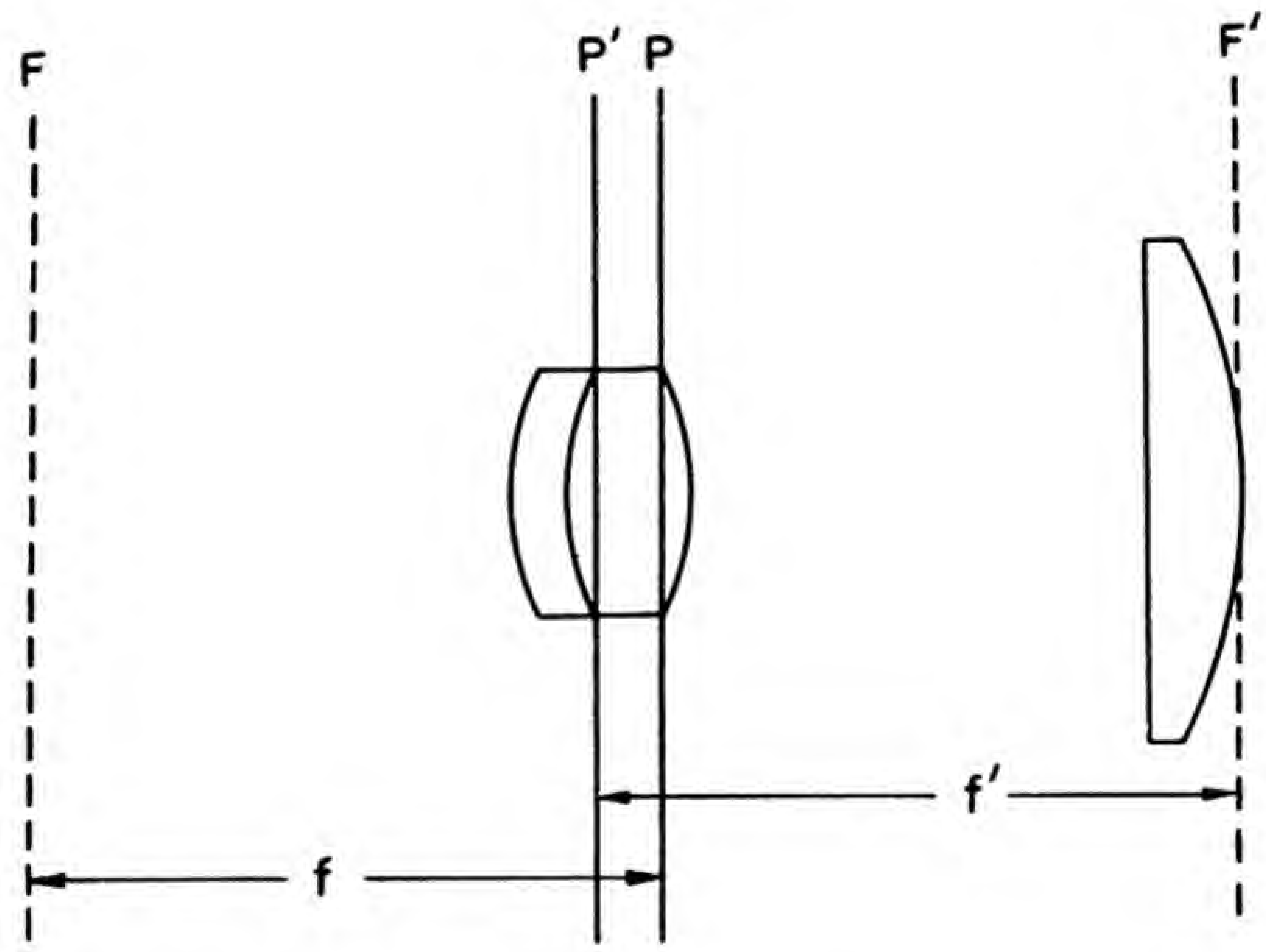


Fig. 6 — Position of achromat and field lens in circumference head.

tive has been named the "circumference head" and may be used satisfactorily for a quick view of a long length of tube.

In the circumference head the distance between the achromat and field lens was chosen so that the image plane would be at the last surface of the field lens. It can be seen from Fig. 6 that the rays from infinity will focus at the last surface of the field lens and that the focal length of the objective combination is equal to the focal length of the achromat, which is 37.1 mm.

The characteristic of the objective which permitted such great depth of field was its ability to focus near and far objects within a small circle of confusion. The image plane of the objective lay too near the last lens of the objective to be checked experimentally. Two

Table 3—Resolution of Circumference Head

	a′, cm		Δa′, cm	
a, cm	Theoretical	Experimental	Theoretical	Experimental
10.0	32.76	32.93		
20.0	31.56	31.97		
∞	30.67	30.93	2.09*	2.0*

*For (a = 10.0) − (a = ∞).

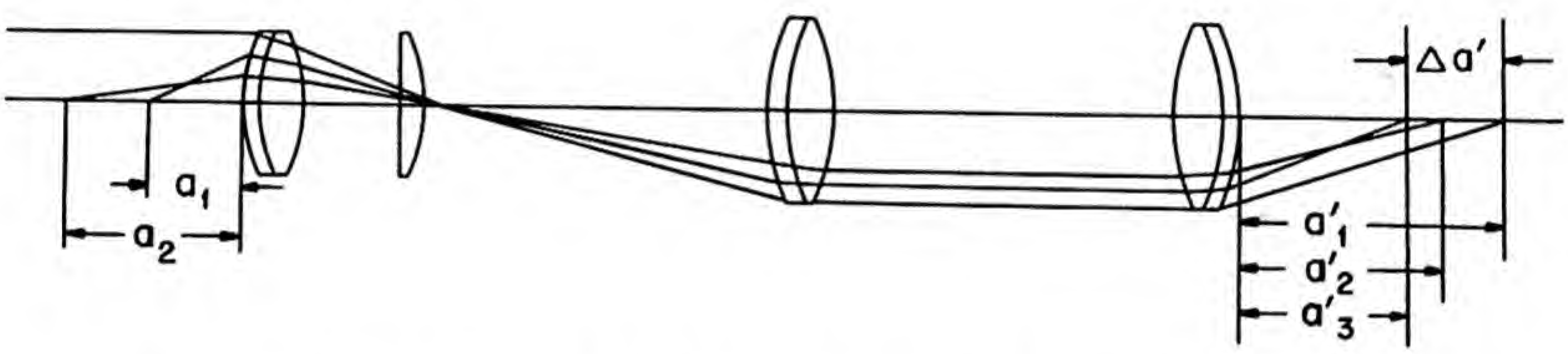


Fig. 7—Arrangement of achromats used to check depth of field.

achromats were placed in front of the objective in the positions they would occupy in the borescope, and images of different object points formed by this system were checked theoretically and experimentally (see Fig. 7).

Object points 10 cm, 20 cm, and a few hundred feet away were used in the experiment. This last distance was figured as infinity. The result checked very closely and proved that this objective was capable of nearly universal focus. The diameter of the circle of confusion, Δa′, is small enough to permit accommodation by the eye. The results are shown in Table 3.

Since experiments show that the lens combination was relatively free from aberration, no theoretical calculation of aberration was necessary.

7. BORESCOPE CONNECTORS

The bronze connecting device mentioned in Sec. 6.1, in addition to having a watertight window, is so constructed that an electrical connection can be made with the other sections of the borescope to

provide a conductor to carry current to the 21-cp lamp in the borescope head. The other electrical conductor is provided by the stainless-steel borescope tubing. To make the mechanical connection between borescope sections watertight and rigid, a rubber gasket is retained in the slotted bronze connecting part of the borescope head. A ratchet-carrying connector portion of stainless steel is soldered into one end of each lens-carrying borescope section. When complete, the other end of each standard section has soldered in it a slotted bronze connecting device similar to the one in the borescope head except that the plastic window is omitted.

8. STANDARD BORESCOPE SECTIONS

The standard borescope sections are of stainless-steel tubing 1⅜ in. in outside diameter and are made in 4- and 8-ft lengths. The standard sections contain plastic achromatic lenses of approximately 12 in. focal length distributed in a standard spacing arrangement so that, when any standard section is connected to the borescope head and inserted in a tube, the wall of the tube is at a distance from the nearest achromat equal to its focal length. The other lenses in the standard sections (there are two lenses in a 4-ft section and four in an 8-ft section) are spaced so that the image formed by the last lens of the section will be at a distance from the first lens of the next-attached standard section equal to its focal length. Each standard section is joined by the borescope connectors to the sections which precede and follow it.

9. MOVING THE BORESCOPE

Since the borescope must be moved through a watertight gland, manual operation is difficult. However, for applications employing only a few borescope sections, a crossarm that can be moved manually is provided. Otherwise, a crossarm is used which is moved over a carriage by a motor-driven gear box. By means of control switches and knobs, the standard borescope sections and head can be rotated in the tubes, and, by means of a pinion engaging a rack on the borescope carriage, the borescope can be advanced or withdrawn in a tube. Since the tubes are to be water-filled, a cap, designed to clamp over a tube nozzle and containing a gland for the borescope to pass through, is mounted on one end of the borescope carriage.

10. BORESCOPE ATTACHMENTS

In addition to the standard arrangement of borescope parts, other attachments and fittings have been provided in order that a relatively

short portable borescope can be assembled for use at the discharge face of a pile. The instrument consists of an auxiliary crossarm that may be connected by the usual watertight borescope joints to 4- and 8-ft standard sections. The portable borescope may be inserted through a portable gland assembly which may be attached to the flanges on the rear face of the pile. This combination may be used to inspect the inside of the ribbed aluminum tubes of lengths of 12 ft or more if necessary.

Paper 2.2

EXPERIMENTS ON A BORESCOPE HEAD*

By George S. Monk

A customary manner of inspecting the inside of a tube is to have a mirror mounted in front of the objective end of the borescope and set at about 45 deg in order that the wall can be seen. To see the entire wall at any part of the tube, the operator must rotate the instrument on the axis of the tube through 360 deg. If the field of view covers only about half a quadrant, eight positions are required to look all around the tube. This must be repeated for every position along the tube. In order to see more of the tube at one time, a circumference head (see Paper 2.1) is used. This is simply an objective pointing straight down the tube; it is commonly surrounded with a ring of midget lamps for illumination.

The borescope must have considerable range of focal adjustment to enable the operator to focus on parts of the tube at different distances from the objective. Obviously that part of the tube which is nearest the objective will have the largest magnification and the best illumination. On the other hand, a wide angle of view is required to see this part.

Because the borescope must be small in diameter, there are several inherent limitations to the field of view. In borescope No. 1, the aperture stop is one of the field lenses along the main part of the instrument. In borescope No. 2, which must be sealed against water (see Paper 2.1), the aperture stop is any one of the connectors between sections. This limits the field of view to about 24 deg. With this limitation, no part of the wall closer than about 3.75 in. to the objective can be seen, and then it can be seen only at relatively large angles of incidence. Although trained judgment permits a fair inter-

*This paper is based on Report CP-2413, Nov. 23, 1944.

pretation of what is seen at such large angles, a more normal view would be desirable.

An obvious procedure is to mount a conical mirror in front of the objective, as shown in Fig. 1. The disadvantage of this system is that this surface introduces aberrations, principally astigmatism, which distort the image beyond recognition.

A degree of correction can be made by introducing a toric surface in place of the surface of a right cone. Considering a zone element e

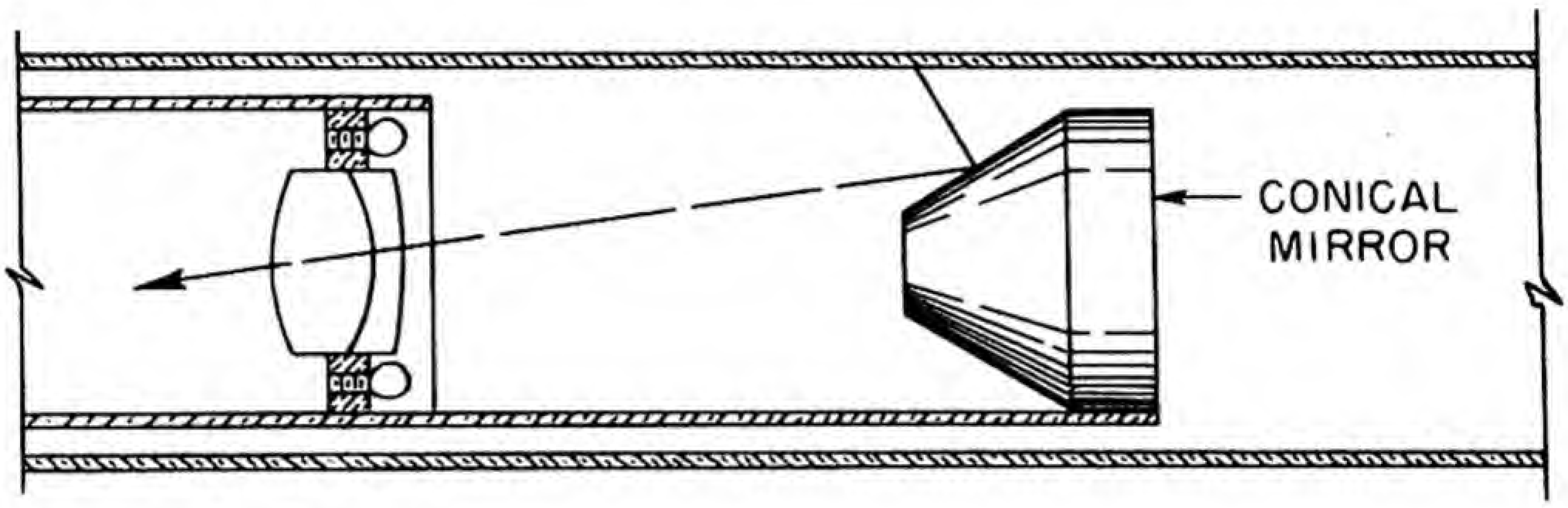


Fig. 1—Circumference-viewing head with conical mirror.

(Fig. 2) of such a surface, for an object distance s, by simple theory the two astigmatic image distances s_1 (primary) and s_2 (secondary) are given by

$$\frac{1}{s} + \frac{1}{s_1} = \frac{2}{r_1 \cos i}$$

and

$$\frac{1}{s} + \frac{1}{s_2} = \frac{2 \cos i}{r_2}$$

where r_1 is the radius of curvature (in a right section) of the surface of revolution and r_2 is the distance from the axis of revolution of the tore to the element of surface. The angle i is assumed to be not very large. To eliminate astigmatism, s_1 must equal s_2; therefore

$$r_2 \cos i = \frac{r_2}{\cos i}$$

or

$$r_1 = \frac{r_2}{\cos^2 i}$$

As an example, suppose that the angle of incidence is 45 deg and $r_2 = 0.8$ in. Then $r_1 = 0.8/\cos^2 45$ deg $= 1.6$ in. (approximately). Obviously, however, r_1 will vary with the position of the surface element, and the best definition will be for objects nearest to the outer run of the tore. The definition can be increased by decreasing r_1 continu-

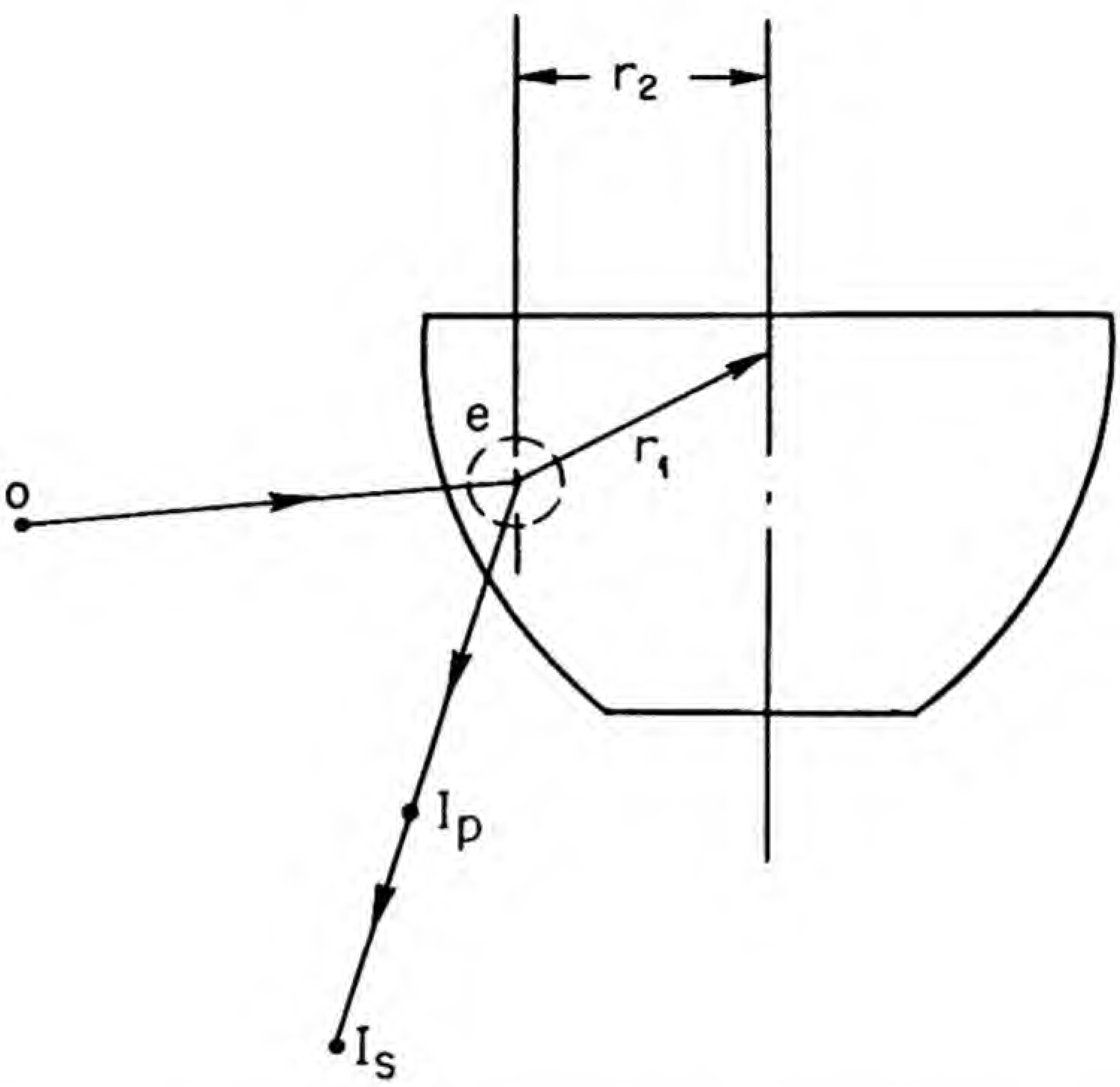


Fig. 2—Toric-surface mirror for astigmatic correction.

ously from the outer to the inner diameter of the tore. The theory is only approximate, and modification by trial and error yields marked improvement.

A limitation on the use of this device is that vision is restricted to that part of the tube mirrored in the tore. This can be overcome in part by varying the angle or by moving the tore away from the objective until part of the tube is seen directly. The image of a small area of the tube wall could then be seen from two sides at once, which would permit some estimate of the depths and shapes of the pittings.

Another limitation is on the illumination. The mirror surface is convex and hence divergent. The cone of rays from any object point is much larger than the objective, and therefore light is lost. This is partly compensated for by the increase in illumination of the walls by reflection from the toric mirror.

Illumination by a ring of lamps around the objective is not the best type of illumination because sharp contrast is destroyed by the multi-

plicity of light sources. A single concentrated source is much better. For this reason the following arrangement has been considered:

Projecting from the borescope frame about the objective is a rib of sufficient rigidity to carry a 21-cp lamp with its filament toward the objective as shown in Fig. 3. Directly between the lamp and the objective and close to the lamp is a mirror at 45 deg. Thus the observer has an annular view of the tube similar to that obtained with a cir-

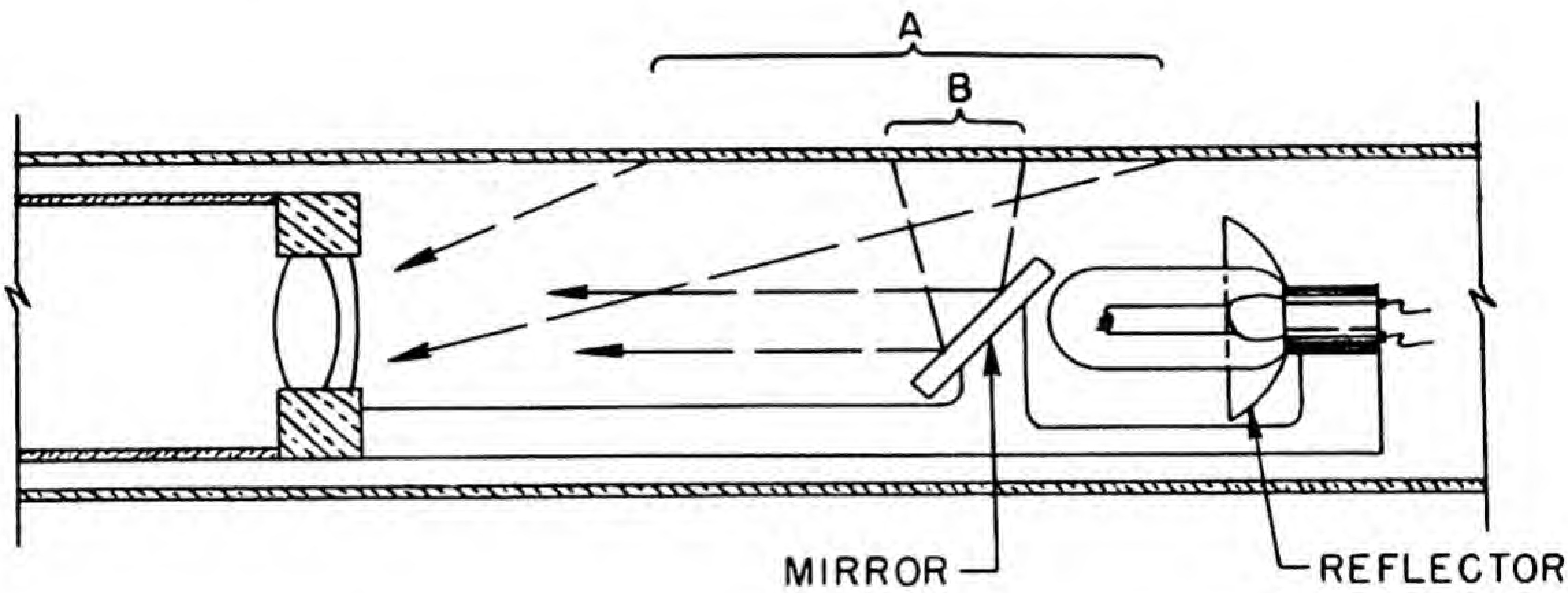


Fig. 3—Circumference-viewing head with small plane mirror and shielded lamp. Area A is viewed directly on circumference; area B is viewed with mirror.

cumference-viewing head, and at the same time he has a view of a limited portion just as obtained by an ordinary right-angle head. There will be, of course, a small portion of the circumference obstructed by the rib which holds this contrivance, but a slight turn of the borescope permits a view of this portion.

This arrangement is relatively fragile and likely to be damaged, but it is thought that its optical advantages make it a desirable unit. In order that the same region may be seen directly and in the mirror simultaneously, the mirror probably must be set at some angle other than 45 deg, but this depends on the design of the entire unit.

A modification of this system could be a movable mirror, which could be swung so that its surface is horizontal when it is not needed. The advantage would be that the mirror could be larger and/or closer to the entrance pupil of the system, thus permitting view of a larger area in the mirror. On the other hand, this involves electrical control of the movement and adds to the complication of construction in the electrical system of the borescope.

Paper 2.3

PERISCOPE FOR DISCHARGE AREA OF A PILE*

By George S. Monk and W. T. Jaycox

[Ten years ago, when this instrument was built and this paper was written, little was known of the probable coloration of the lenses. It was hoped that, with the shielding provided, the instrument would serve usefully for some weeks; actually, its life was measured in hours. This paper is included in this volume because of the useful and perhaps novel features of construction. With the noncoloring optical materials now available the life of the periscope would have been much greater.]

1. DESCRIPTION AND OPERATION

1.1 Introduction. A pile periscope made in Chicago was built with the expectation that it could remain continuously installed in the ceiling shield of the pile room. In order to ensure satisfactory baffling of radiation, all space in the periscope not occupied by the optical path is filled with lead shot, paraffin wax, solid lead, the metal casing of the instrument, and water. The lead should be free from antimony and other impurities. The absorbing materials are chiefly in the long vertical part of the periscope which occupies the space inside the concrete shield. No special screening has been attempted above the periscope; but the metal casings are unusually massive for an optical instrument, and there is an offset so that the operator will not be directly above the hole through the shield.

1.2 Optical Path. The arrangement of the optical path and some explanation are given in Fig. 10, Paper 1.1. An additional feature of this periscope is the use, as an extender, of a tube of water with a lens at each end. The tube of water constitutes a third telescope;

*This paper is based on Report CT-1242, January 1944.

since the ratio of the focal length of the lenses in this third telescope is 2 to 1, the entire instrument has approximately twofold magnification.

1.3 Illumination. If possible, all optical parts are coated with low-reflection materials. The water in the middle telescope, when clean and fresh, has a low absorption of a few per cent. In spite of this precaution the transmission of the entire instrument is rarely more than 30 per cent. Moreover, the objects to be viewed have very low reflectivities, and therefore the illumination factor must be high. The writers' experience has been that objects must have falling upon them at least 50 ft-candles of white light to be seen distinctly, and from 150 to 200 ft-candles of illumination is more desirable. This factor of illumination is important.

1.4 Coloration of Glass. (See Paper 3.2.) If properly installed, no focusing other than a motion of the eyepiece should be necessary. The normal position of the instrument should be such that the fin (containing lead and paraffin wax), extending 18 in. below the objective, will hang next to the face of the pile. Radiation will then be required to pass through as long a path as is possible with this instrument before reaching any of the glass components. The most vulnerable lens is the objective element, and provision has been made for replacement of this element if coloration should occur. The replacement requires careful dismantling of the lower end of the periscope.

1.5 Viewing-mirror Control. The viewing mirror is rotated by movement of the control lever mounted on the horizontal crossarm of the instrument. The movement is carried through three gear trains with a great speed reduction, permitting the mirror to be used with a very slow and steady movement of the control. When the control is at 0 deg, the viewing mirror is in a vertical position and will rotate 90 deg in each direction.

The optical and mechanical details for the completed instrument are shown in Fig. 1.

2. WATER SYSTEM

The water column is in a brass cylinder tinned on the inside. A copper tube $\frac{3}{16}$ in. in diameter, which is soldered in at the top, affords an air vent or water overflow. A second copper tube, which is passed through the wall of the water cylinder at the top, is bent so that its outlet is directly below the upper lens. A third copper tube similarly soldered into the water cylinder goes to the bottom with its end directed toward the lower lens. These two last-mentioned tubes are designed to afford a means of shooting a jet of water with as much impulse as possible across the faces of the lenses so as to remove

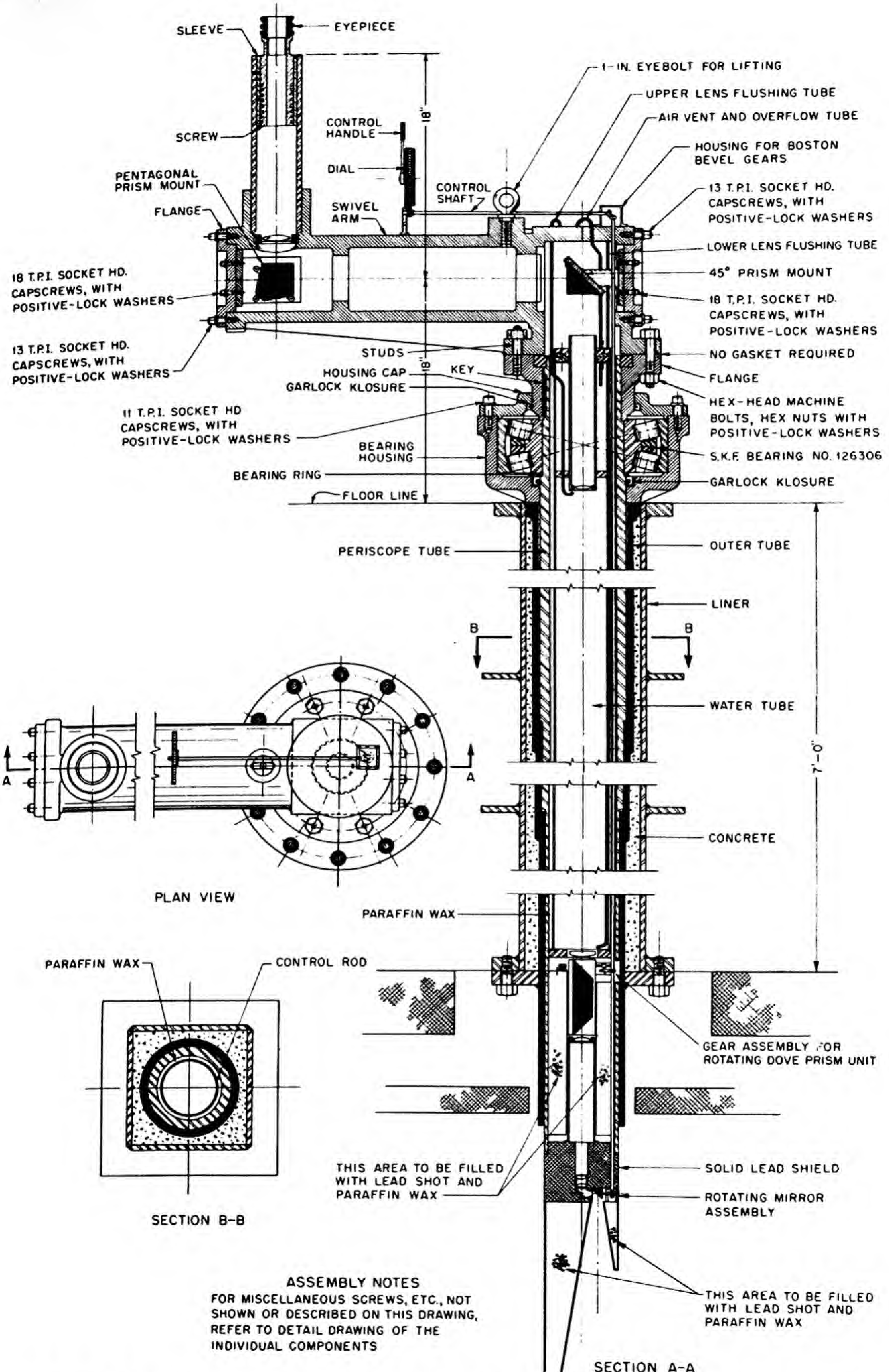


Fig. 1—Mechanical and optical details of the discharge-area periscope.

the obstacles to clear vision. In the case of the lower lens, these obstacles may be particles of foreign matter in the water. In the case of the upper lens, these obstacles will probably be bubbles. A special water bottle with compressed-air connections is provided for injecting a jet of water for the removal of dirt or air bubbles.

The water-tube outlets for the upper and lower lenses are operated by means of a quick-action valve located on the side of the crossarm and directly connected to a two-way valve. The direction of the flow is indicated on the two-way valve by arrows.

When the valve is set for the lens chamber desired, the lens is flushed, by means of the quick-action valve, with an impulse of water under 10 to 15 lb pressure.

The water may be drained from the tube through the lower outlet of the quick-action valve by applying 3 to 15 lb air pressure through the overflow lead and by opening both the outlets near the lower lens and the quick-action valve.

To refill the water tube, water is passed under pressure through the lower outlet of the quick-action valve, and, by intermittent operation of the two-way valve, is sent over the upper and lower lenses. The water level can be determined by observation through the eyepiece. Water is added to the tube until the upper lens is submerged. If bubbles are present, the lenses should be flushed. The capacity of the water tube is approximately 19½ qt, and under no circumstance should the tube be filled to overflowing. The water used must be double-distilled or the equivalent.

Paper 2.4

THE BINOCULAR PERISCOPE*

By George S. Monk

The absence of stereoscopic vision is a limitation on the usual periscope (see Paper 1.1). To offset this, two identical periscopes can be used, one for each eye. The amount of stereoscopic effect can be

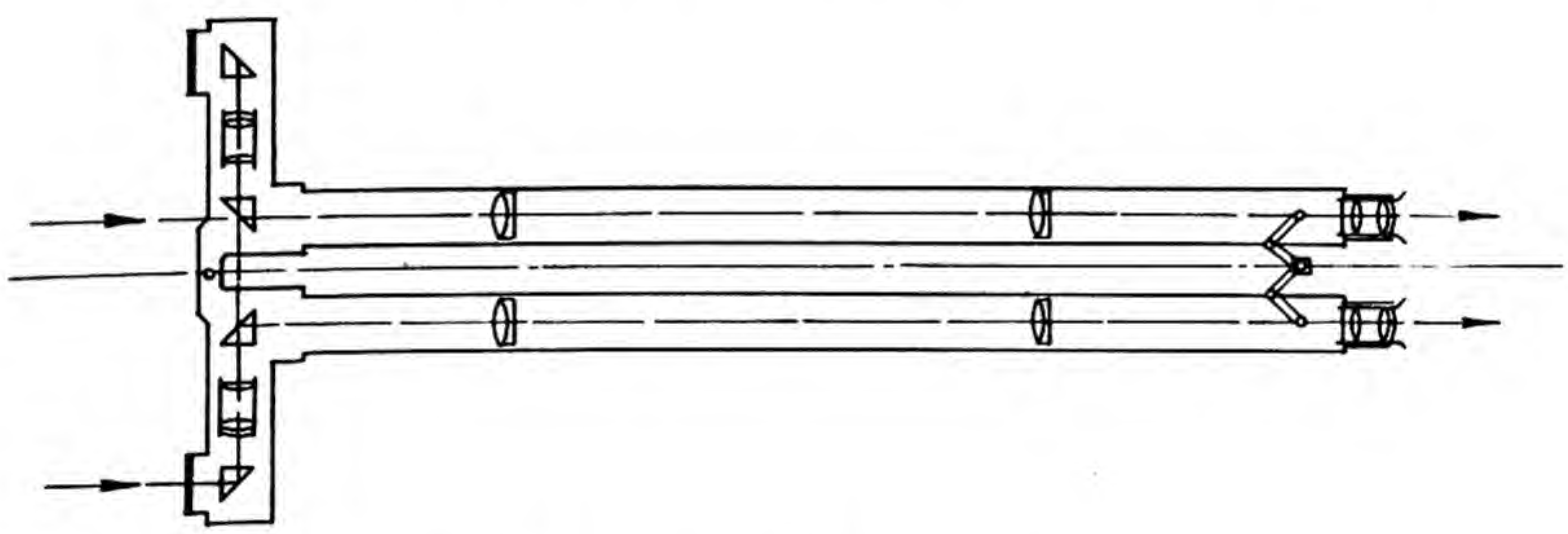


Fig. 1—Binocular periscope.

controlled by the angle between the two tubes. If each is pointed at a given object position, the stereoscopic effect is no different from that of the unaided eyes. If the tubes are spread apart at the objective ends, the effect will be enhanced, but the fields will overlap only in part, and the field common to both eyes will be reduced. This can be overcome by constructing the entire instrument as shown in Fig. 1.

The instrument can be adapted for viewing objects lying on the bottom of a pool of water, without causing disturbances and reflections,

*This paper is based on Report CP-2296, Oct. 31, 1944.

simply by submerging the objective ends. Water, with an index of refraction of 1.33, will make a submerged object ½ in. high seem to be only three-fourths as large or ⅜ in. The use of this design serves not only to correct this foreshortening of objects, but, if need be, to enhance the stereoscopic effect. Thus the examination of surface objects seen below water may be improved.

Paper 2.5

THE CORNER PERISCOPE*

By George S. Monk, W. H. McCorkle, and Associates

ABSTRACT

A description is given of the construction and operation of an unusual type of motor-controlled periscope for inspecting the discharge area of a pile. The arrangement of the instrument is depicted by an outline installation drawing.

1. INTRODUCTION

A centrally located hole 3 ft square was left in the rear wall of a pile discharge area for the insertion of suitable optical devices. A fly-eye was placed in this hole. This was a circular cylindrical tank with a glass window on the outside end, and on the inside end four North American Aviation negative plastic lenses (sold as surplus) were so placed that together they gave a reduced view of a large portion of the rear pile face. The circular tank left the corners of the square hole free, and for the upper left-hand corner, looking through the glass window, a "corner" periscope was built. An outline plan of this instrument is shown in Fig. 1.

2. DESCRIPTION OF INSTRUMENT

The corner periscope is a scanning periscope capable of viewing the entire rear face of the pile. The scanning head rotates about a horizontal axis through 360 deg in either direction. It is also equipped with two mirrors in front of the objective. The first turns on an axis which is perpendicular to the axis of the periscope objective and lies

*This paper is based on Report CP-2437, Jan. 2, 1945.

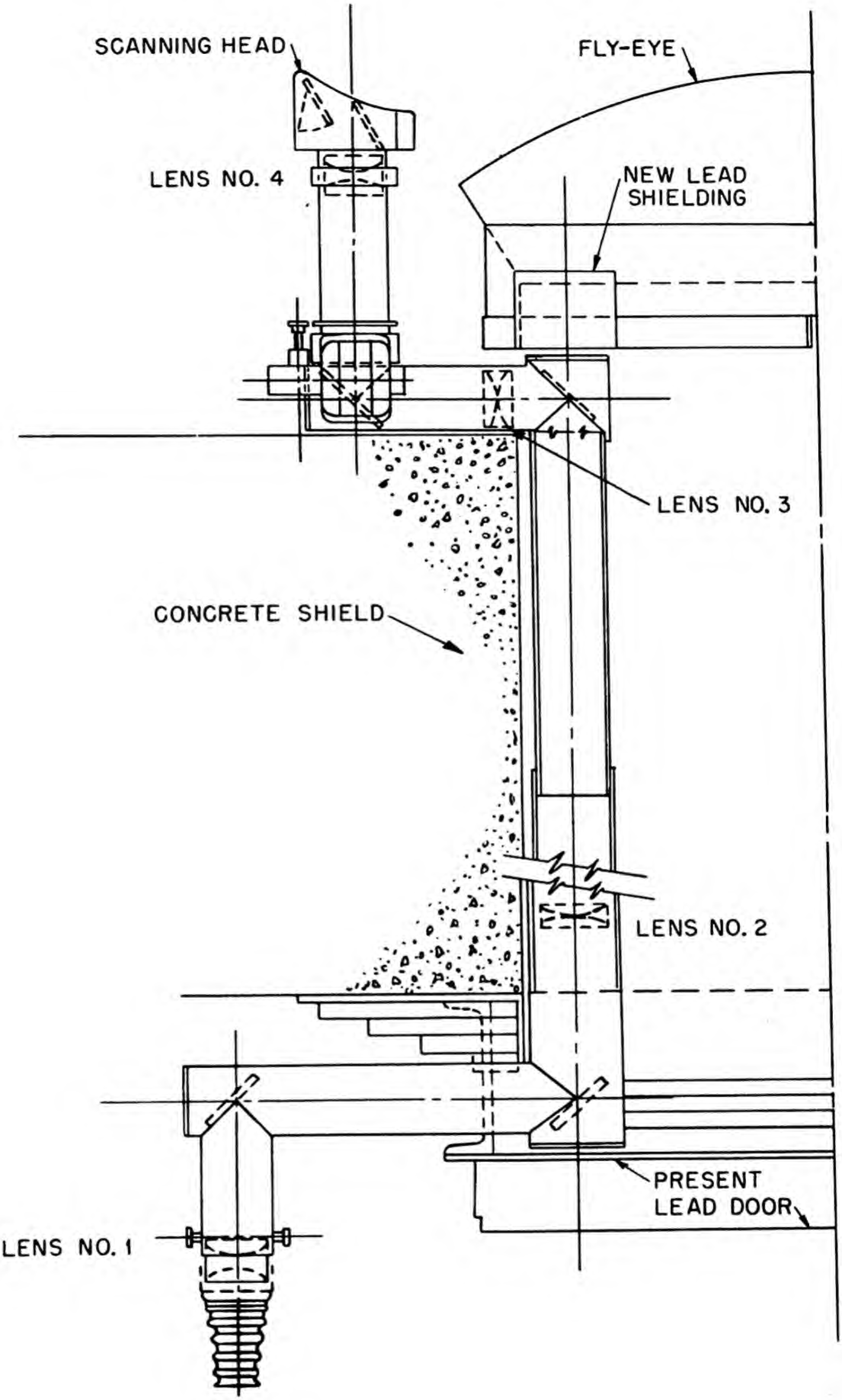


Fig. 1—Corner periscope.

in a plane parallel to a plane containing that axis. The second mirror is fixed in the scanning head. This arrangement of two mirrors ensures that, no matter how the head turns, objects are seen in their normal positions. Also, the four mirrors inside the periscope are so arranged in pairs that there is no revision of the image. The observer thus sees things as if he were standing just inside the discharge area and looking about him. For any setting of the scanning head, the angle of view is about 18 deg. The magnification for a position on the pile face directly opposite the periscope is nearly 3. The magnification for an extreme corner of the pile is about 1.25. The magnification factor depends partly on the positions of the first and second erector lenses of the periscope; the factor can be modified to some degree.

All the lenses are plastic. The aperture of each is about 2.75 in. The objective and eyepiece have unusually large pupils. The exit pupil of the system is ¾ in. in diameter and is about 4 in. from the eyepiece exit face. Although its size results in a slight reduction of brightness, ease of observing is enhanced. With six mirrors in the system, it was considered desirable to use aluminum surfaces. Assuming a maximum reflectivity of 90 per cent for each of these, the light transmission can be no greater than 0.46. This is reduced somewhat by surface reflections. With all but four lens surfaces coated, it is estimated that the transmission is about 30 per cent. Although this is somewhat lower than the best glass periscopes, it is remarkably good. The use of plastics was, of course, dictated by the radiation hazards, and the number of reflections was dictated by the necessity for shielding personnel.

3. OPERATION OF INSTRUMENT

Operation of the rotating scanning head and the scanning mirror, movable in the hand, is accomplished by means of electric motors controlled through switches placed in a switch box conveniently located near the mechanical focusing device (rack and pinion), which moves the eyepiece of the instrument.

Two switches are provided, each constructed to provide forward, off, or reverse motion of the respective motor to which it is connected by suitably insulated wires passing through the body of the periscope and running along the lower inside surface of that part of the instrument situated in the 5-ft-thick concrete wall. The motor which rotates the scanning head at a rate of ½ rpm is a reversible 1/20-hp motor attached to the objective face of the 5-ft-thick wall by a steel bracket. The motor communicates motion to the scanning head through a chain and sprocket.

The movable scanning mirror is caused to sweep back and forth over an angle of approximately 85 deg by a small ½-rpm, reversible Haydon motor which imparts motion to the mirror by means of a link and crank mechanism. Thus, by means of the focusing nut and the motor-control switches, any desired part of the discharge face may be readily brought into focus by the operator; if some point of interest is inadvertently passed by, a reversal of the proper motor or motors will readily return it to the field of view.

Paper 2.6

A VISUAL INSPECTOR FOR SLUGS*

By M. C. Leverett, W. T. Jaycox, and George S. Monk

ABSTRACT

The construction and operation of a device for manipulating and viewing discharge slugs are described. The instrument incorporates in one unit radiation shielding for the operator, mechanical means for manipulating a slug, illumination, and a periscopic optical system for viewing the slug.

1. INTRODUCTION

Personnel must be protected during the detailed inspection for corrosion or other deterioration of a slug removed from a pile. Manifestly, one way of doing this is to leave the slug at the bottom of the discharge well or the canal and look at it with an underwater periscope. Although this method has a time advantage, the controlled manipulation of the slug is difficult. Moreover, although the underwater periscope has distinct advantages for operations such as sorting or selection, it must be used in an area in which other activities may be going on. Consequently a lead box was designed which could be lowered to the bottom of the canal; a selected slug could be put in, and the box could be closed and hoisted through an opening into the hot laboratory.

2. DESCRIPTION AND OPERATION OF INSTRUMENT

The box has five essential features: (1) thick lead walls to prevent escape of radiation, (2) a mechanical system for rolling and sliding

*This paper is based on Report CE-2384, Nov. 17, 1944.

the slug so that the entire surface may be inspected, (3) a cradle to facilitate handling, (4) an optical system, and (5) means for illuminating the slug.

The box has shape and dimensions such that the thickness of lead between any point on the slug and the outside is at least 6½ in. This is possibly violated in the direction through the lighting units, but to give additional shielding a slab may be provided behind the box. All the electrical plugs and optical parts which project from the faces of the box are removable or recessed.

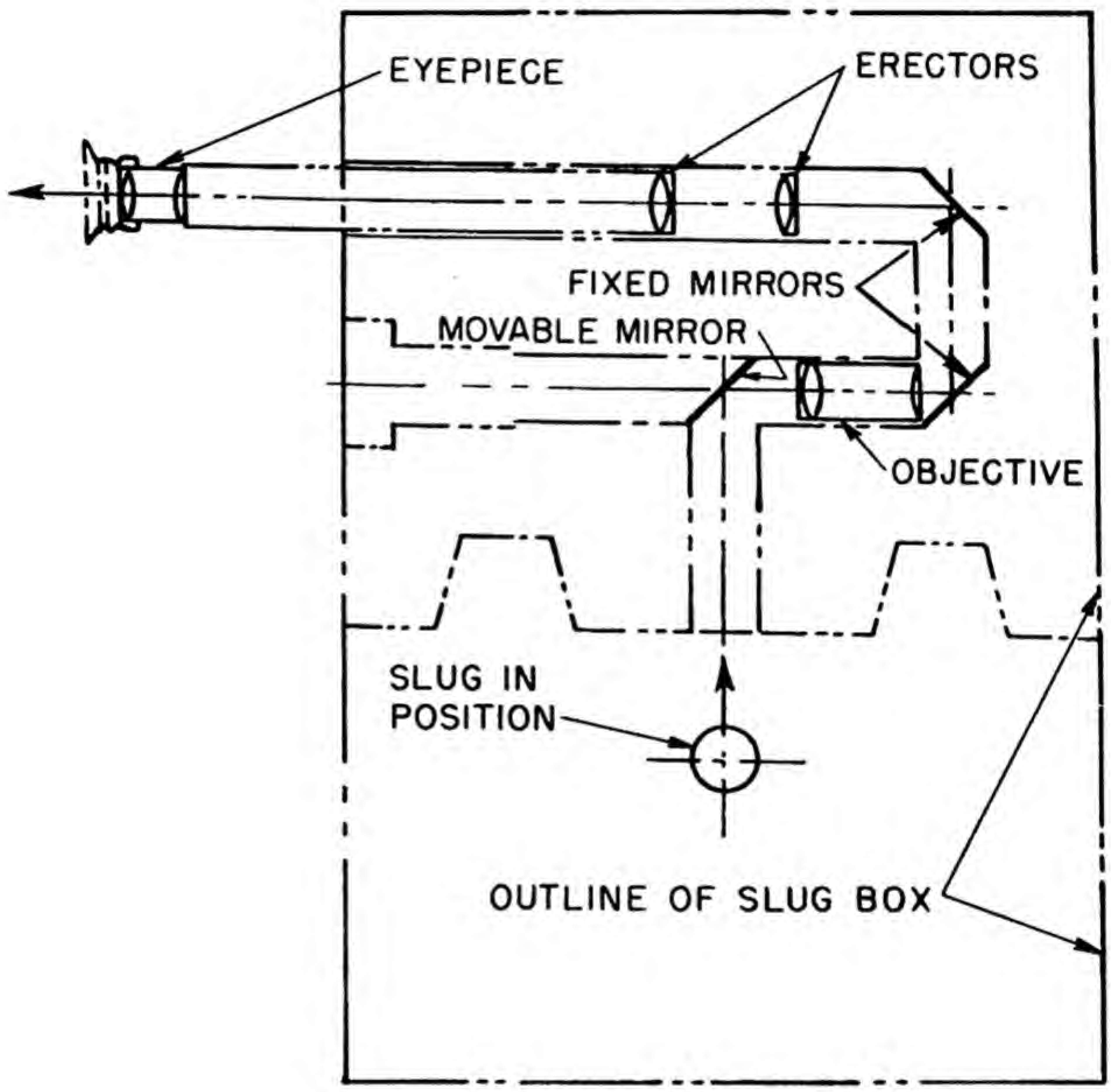


Fig. 1—Outline of slug box and arrangement of optical system.

The optical system has in it the lens train of a standard periscopic sight (see Paper 1.1). The detail is shown in Fig. 1. To baffle radiation, the optical path has three right-angle bends. Two bends would probably have been ample, but the third provides that the eye end of the periscope is located conveniently for an operator sitting or standing in front of the box. The mirrors are constructed of Stellite. Everything in the optical train except the second telescope is enclosed between watertight windows. The second telescope fits into a hori-

zontal tube in the lid of the box and can be removed when the box is lowered into the canal. The lower watertight window, which is plastic, is below the scanning mirror in the fan-shaped opening above the slug. It is provided with a wiper to remove drops of water which might otherwise interfere with clear vision. The wiper is operated by a rod extending to the right-hand end of the box.

For controlling the movement of the slug within the box, a pair of brass rollers 7/16 in. in diameter is mounted near the bottom of a trough 14 in. long and 1½ in. wide. These two horizontal rollers are geared together in direct ratio with a detachable crank which fits in a keyway on one of the rollers. By means of an idler gear the two rollers rotate in the same direction when the handle is turned, and a slug lying on these rollers will rotate on its horizontal axis.

For propelling the slug along the 14-in. length of the trough, three wheels, each 1½ in. in diameter, are mounted between the horizontal rollers; the shafts are run to the front of the box, where a keyway on each shaft permits attachment of a control crank. Each of these three wheels has a segment cut out of the rim and is mounted with a rubber tire. When the flat portion of the rim is uppermost, the clearance allows the slug to rotate freely on the horizontal rollers; when one of these wheels is turned, however, the rubber engages the slug and carries it along in either direction until one of the other wheels can continue its travel.

During construction of the box it was noted that, after the lead was poured and while the accessories were being installed, the lead flowed slightly. If other boxes of similar mass are constructed, it would be advisable to introduce some reinforcement to prevent this flow.

Shielding tests performed on the viewer indicate that no dangerous radiation intensity exists anywhere on its surface. Operating use discloses only minor opportunities for improvement. One of these lies in the fact that water droplets tend to cling to the Stellite mirrors in the lower half of the box. Also, the ends of the slug, although perfectly visible, could be more easily examined if the level of illumination were higher.

An alternative method for loading a slug into the viewer is as follows: The bottom portion of the box is lowered into the canal, and the slug to be inspected is placed in it while the viewer rests on the bottom of the canal. The operator at the crane control in the hot laboratory then draws up the lower half of the box until it is higher than head level for persons in the canal area and then retires from the hot laboratory while an operator in the canal area causes the crane to draw the slug viewer up into the hot laboratory, using the controls in the canal area for this purpose. Once the lower half of the box has been

drawn up to approximately shoulder height in the hot laboratory, the hot-laboratory operator returns and manipulates the upper half of the box onto the crane and places it on the lower half of the box. This is no less laborious than lowering the whole box into the canal, but it avoids putting the upper half of the viewer under water and makes it unnecessary to ensure that all joints in this half are watertight.

Provision has been made for photographing the slug through the periscope. A specially made camera, using a 3¼- by 4¼-in. film-pack holder, can be fastened to the periscope at the eye end. The tube containing the lens of the camera is slipped over the eyepiece, and the latter is adjusted until a sharp focus appears on the ground-glass screen of the camera. Then the film pack is substituted and exposures are made. Tests on instruments of similar design show that an exposure of between one-tenth and one-fiftieth of a second is sufficient, depending on the lighting of the particular detail to be observed. A long slug may be too close to the objective of the periscope to be photographed in its entirety, but approximately 4 in. of its length can be photographed with a single exposure.

This instrument is a valuable tool for the detailed examination of representative slugs discharged from the pile.

Paper 2.7

UNDERWATER BAR VIEWER*

By W. H. McCorkle

ABSTRACT

A description is given of a device for viewing objects under several feet of water, with resultant magnifications varying over a range from about two to ten times normal viewing size.

1. INTRODUCTION

Under certain circumstances of Project operation it is desirable to view objects submerged in about 20 ft of water and also attain a magnification from two to ten times viewing size at normal distance (10 in.) from the eye. To accomplish this a device known as an "underwater bar viewer" was designed to be submerged in the water and rigidly supported in an auxiliary apparatus by which the object to be viewed could be manipulated and placed in the proper position for illumination and observation through the underwater bar viewer.

2. BASIC CONSIDERATIONS AND CONSTRUCTION

Under the above conditions the problem is essentially one of placing an object at varying distances from a short-focal-length objective lens and of transferring the image formed by the objective lens to the focal plane of a distant eyepiece of short focal length. Since this is very much the same problem as is encountered in the borescope and since lenses and other material used in borescope construction were already in stock, the construction of the underwater bar viewer parallels that of the borescope in many respects (see Paper 2.1). As seen

*This paper is based on Report CP-2969, May 21, 1945.

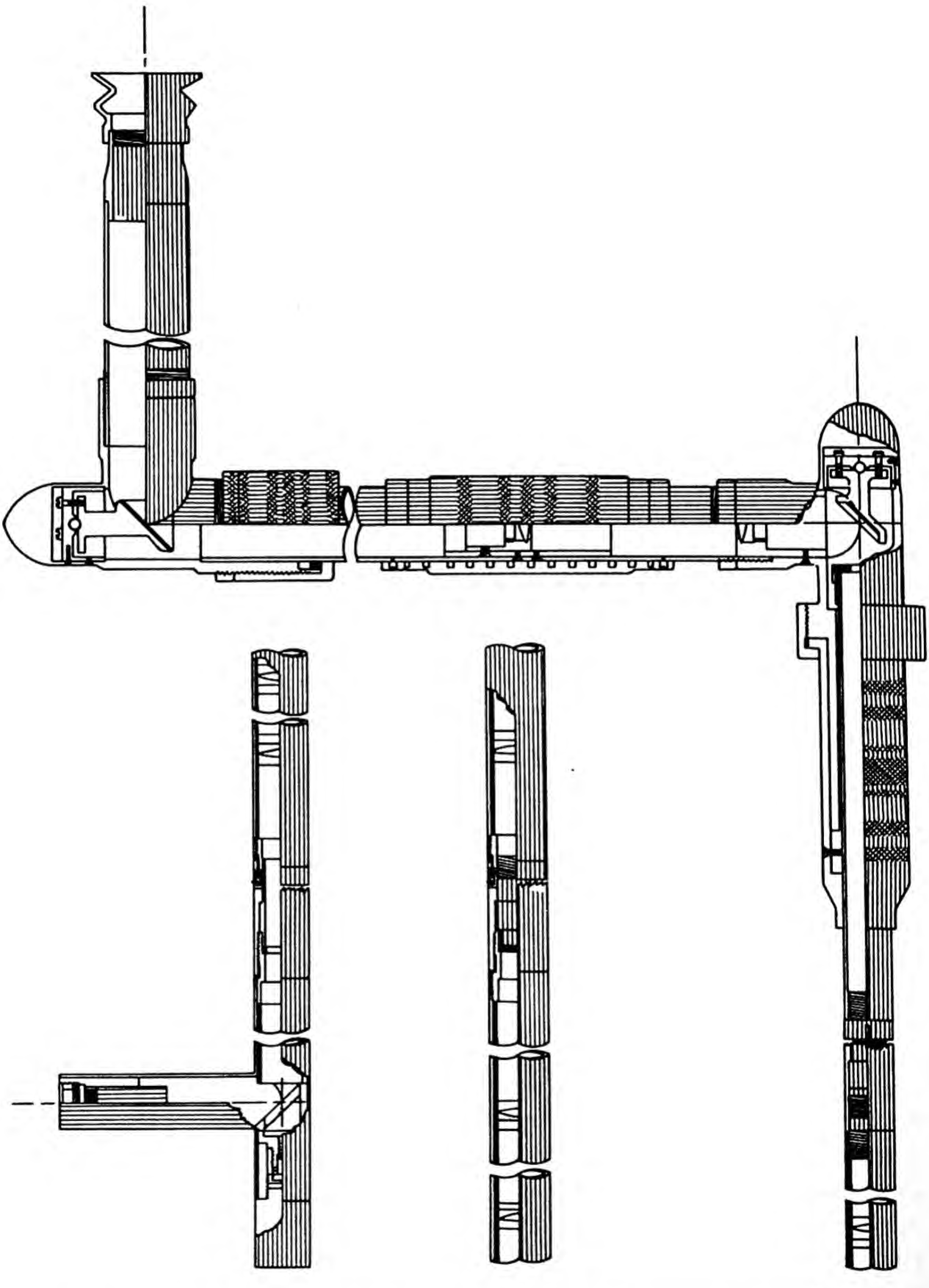


Fig. 1—Broken-away assembly drawing of underwater bar viewer.

in Fig. 1, the instrument consists of an objective section carrying a short horizontal brass tube 1⅜ in. in diameter and about 5 in. long, silver-soldered to a longer vertical tube of the same material and diameter, attached to a threaded pedestal rod in order that the horizontal portion can be supported by the manipulator stand at a distance of 20 in. above the floor of the basin, which is filled with approximately 20 ft of water. The horizontal tube, placed in such a manner that the manipulator can move the object to be viewed between 3 and 24 in. from the free end on a line closely coincident with its axis, carries a short-focal-length plastic objective lens sealed in the tube by a watertight plastic window at the free end of the tube. [This objective lens is the one designed for certain borescope applications (see Paper 2.1).] Following the objective lens in the optical train is a plane mirror of Stellite with a 1-in. minor axis adjusted at the juncture of the horizontal and vertical tubes of the objective section in order that light from the objective lens can be directed upward to the next element of the optical system. The portion of the objective section following the Stellite mirror in the optical train is composed of the elements of a standard 8-ft borescope section with the exception of the insulator and electrical conductor normally carried in the watertight borescope connector. Removal of these parts gives a slightly larger field of view than is possible with a standard borescope section.

Following the objective section is a standard 8-ft borescope section, then a standard 4-ft borescope section, all joined by watertight borescope connectors with the same modification as in the connector for the objective section. At the top of the 4-ft borescope section is attached a universal borescope crossarm containing a Stellite mirror to direct the light received from the standard borescope section into the horizontal focusing part of the crossarm carrying two glass achromatic lenses. The focusing lens passes the light through a totally reflecting prism to form an image in the plane of the eyepiece just as in the case of the standard borescope crossarm.

By changing the position of the object under observation from 24 to about 3 in. from the objective window and by adjusting the focusing sleeve of the crossarm, images with magnifications ranging from about 2 to 15 times may be focused for the observer.

Paper 2.8

THE PERITELESCOPE*

By George S. Monk

To obtain a large field of view and reasonably high magnification, an instrument called a "peritelescope" was designed, by means of which the observer can shift from a periscope of about unity magnification and a 25-deg angle of view to one with a magnification of almost 6 and a 7-deg field. The image is erect at all times.

The optical train is shown in Fig. 1. To obtain a large field, the lens assembly L_2 is swung into the optical train and the erector L_3 is racked upward to focus. To obtain high magnification, L_2 is swung to one side and L_3 is racked downward to focus. Normally, when L_2 is employed, L_1 should be swung to one side. This, however, would necessitate a large and cumbersome mechanism. In planning the optical train it was found that no important loss of definition or increase of aberrations resulted if L_1 were left permanently in place, so long as the adopted spatial relations were maintained. Actually, the presence of L_1 in the large field system serves to increase the field slightly.

It is not necessary to focus by shifting the eyepiece, and the eyepiece should not be removed since the chance of fouling the optical surfaces would be increased. With the large field and unit-magnification system, focusing from a few inches to infinity is possible. With a small field and high magnification, focusing from about 5 ft to infinity is possible. It should be pointed out that objects closer than 7 ft require relatively low magnification. Actually, with the large field system the magnification of an object 1 ft away is about 2, and it rises rapidly as the object is drawn closer.

*This paper is based on Report CP-3111, Aug. 11, 1945.

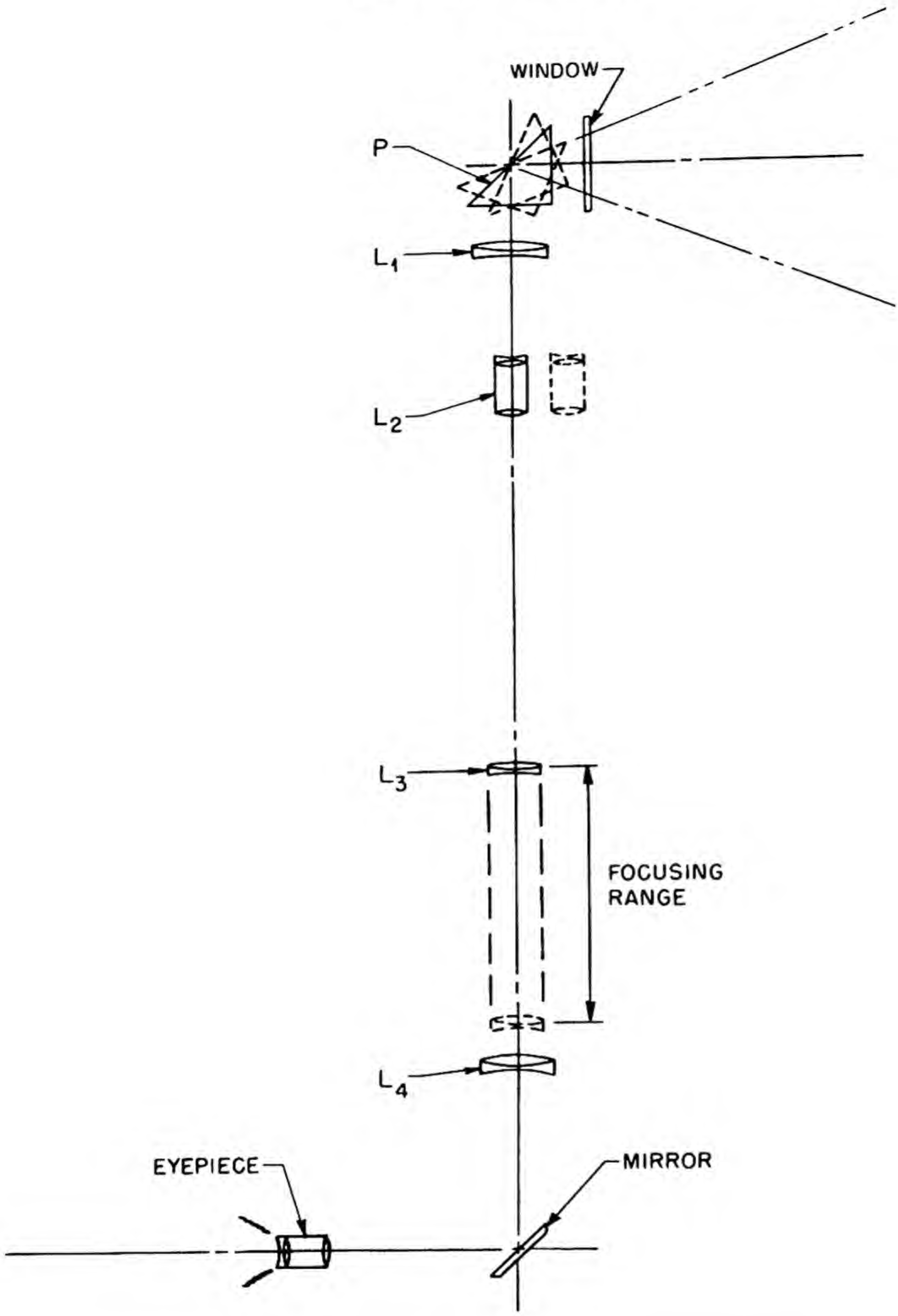


Fig. 1—Optical train of the peritelescope.

Scanning vertically is done by rotating the prism about a horizontal axis. The vertical scanning range is at least 20 deg up and 20 deg down. Scanning horizontally is done by swinging the entire instrument on its stand about the axis of the stand.

Paper 2.9

TYPE D-A PERISCOPE*

By W. H. McCorkle

The type D-A periscope was designed in order that a field of approximately 150 deg could be swept by the scanning device. The close quarters in which the instrument was to be installed required that it be made in three sections. These sections were made of 24 ST aluminum tubing approximately 4 ft long and 4 in. in diameter.

The objective section (Fig. 1) carries the motor-operated scanning device, the objective lens, and the first erector lens. Both the objective and erector lenses are plastic and are 3¼ in. in diameter. An electric-motor-operated scanning mirror was used because the sectional nature of the periscope and the possibility that rapid assembly would be necessary made direct mechanical control inadvisable. Electric current is supplied to the reversible electric motor by three small insulated copper wires running just inside the 4-in.-diameter aluminum tubing. Electric connections are made between sections of the instrument by sliding spring contacts mounted in the connecting joints of the periscope as shown in Figs. 1 and 2.

The eyepiece section (Fig. 2) carries the second erector lens, movable by a rack-and-pinion control for focusing the instrument, and the eye lens placed in a short side tube at right angles to the main body of the instrument. The second erector and eye lens are, respectively, like the first erector and objective lens of the objective section. Light from the second erector is directed into the side tube by a large Stellite mirror in order that the image of the desired object falls in the focal plane of the eye lens. A middle section serves to space the above two sections in such a manner that with all three sections joined together the instrument has a length of approximately

*This paper is based on Report CP-3121, Aug. 22, 1945.

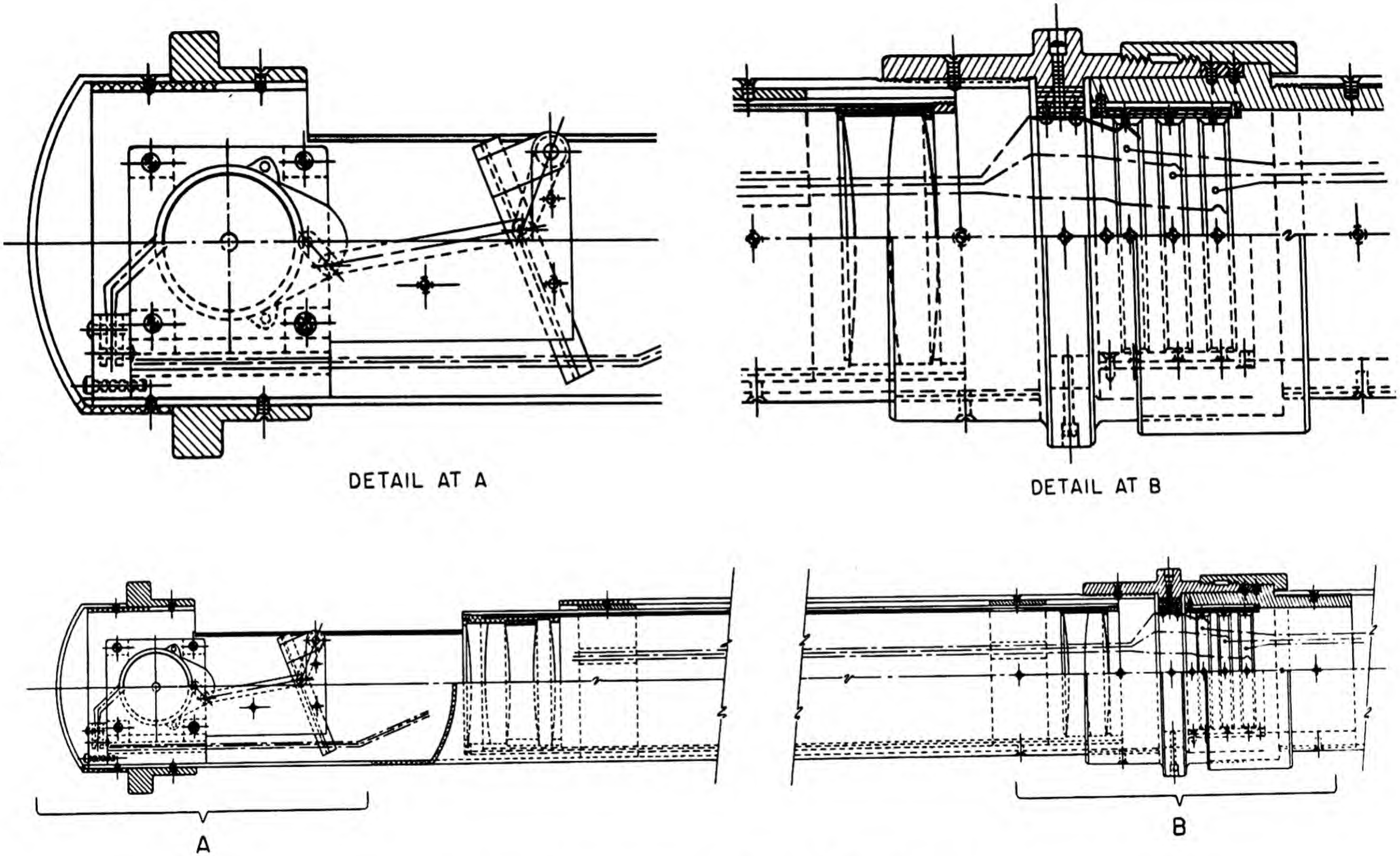


Fig. 1—Objective section of type D-A periscope.

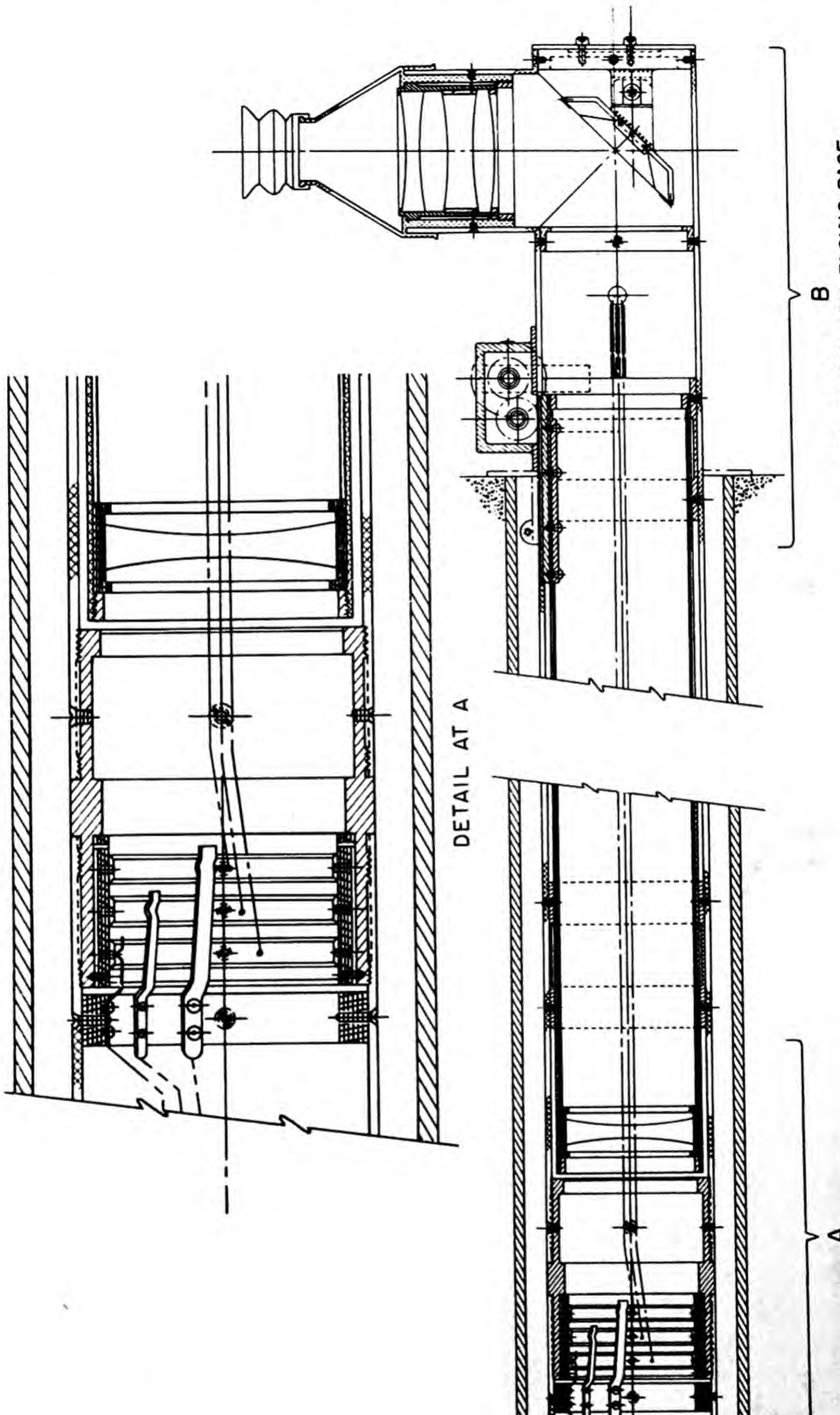
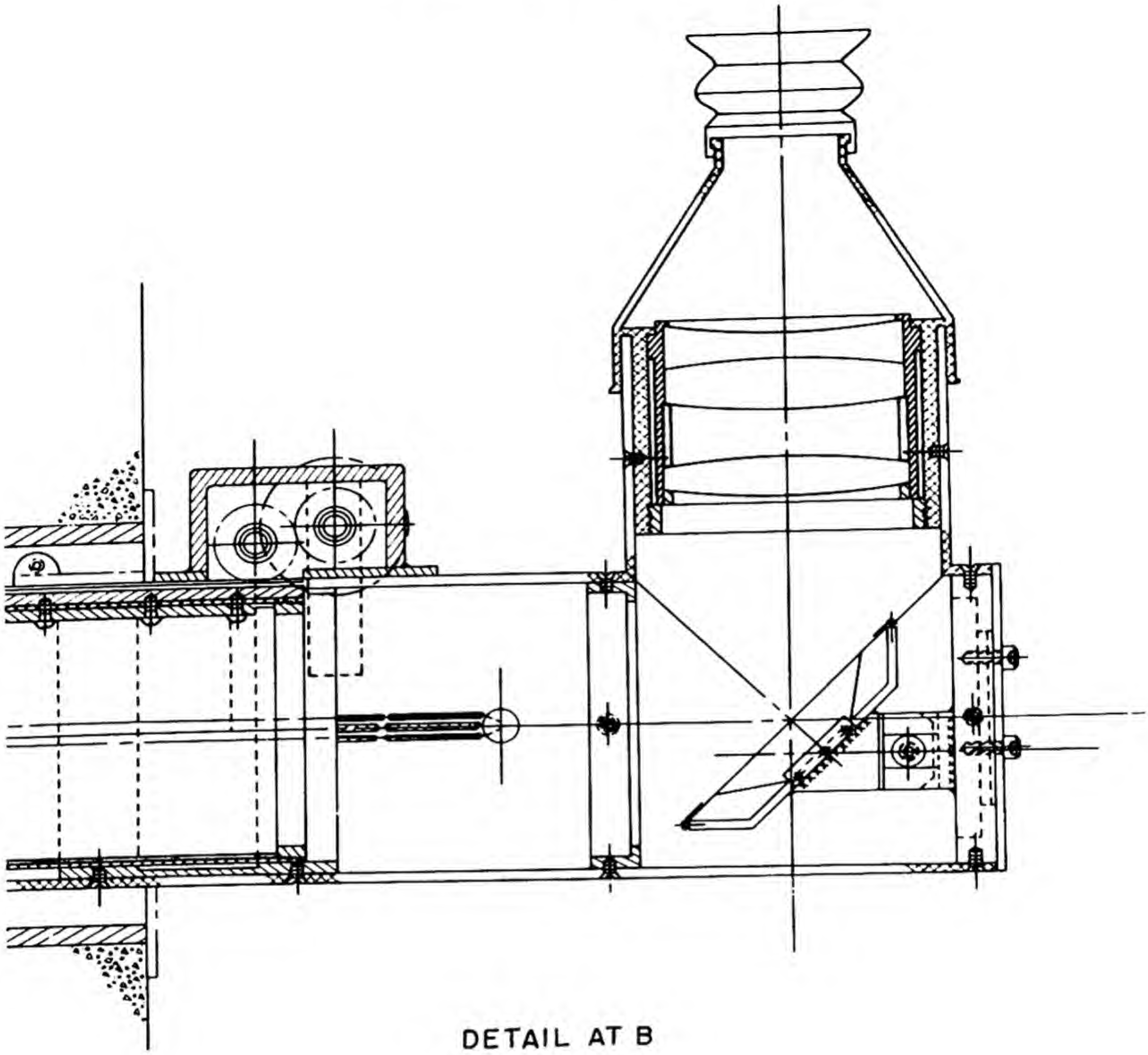


Fig. 2—Eyepiece section of type D-A periscope with adjustable Stellite mirror and focusing control.



DETAIL AT B

12 ft. With the middle section removed and the objective and eyepiece sections joined together, the length of the instrument is approximately 8 ft.

In use the instrument was to be inserted through a stainless-steel tube with openings in the side at the desired vantage points. For sliding the instrument in and out of the large tube, it was considered advisable to have brass bearings surrounding the periscope. Since the instrument is rather large, the connecting joints are necessarily quite large and heavy; to keep the instrument as light in weight and as simple as possible, the connectors for several sections were designed to serve also as bearings between the periscope and the steel-tubing wall. For rapid assembly or disassembly of the instrument, a quick-acting nut for clamping the sections firmly together is incorporated in the connectors; the nut may be tightened with a large spanner wrench.

Paper 2.10

TYPE D-B PERISCOPE*

By W. H. McCorkle

For the close inspection of certain objects that are quite inaccessibly located within a 5-ft-thick radiation shield, a slender borescope-type optical instrument called the "type D-B periscope" was de-

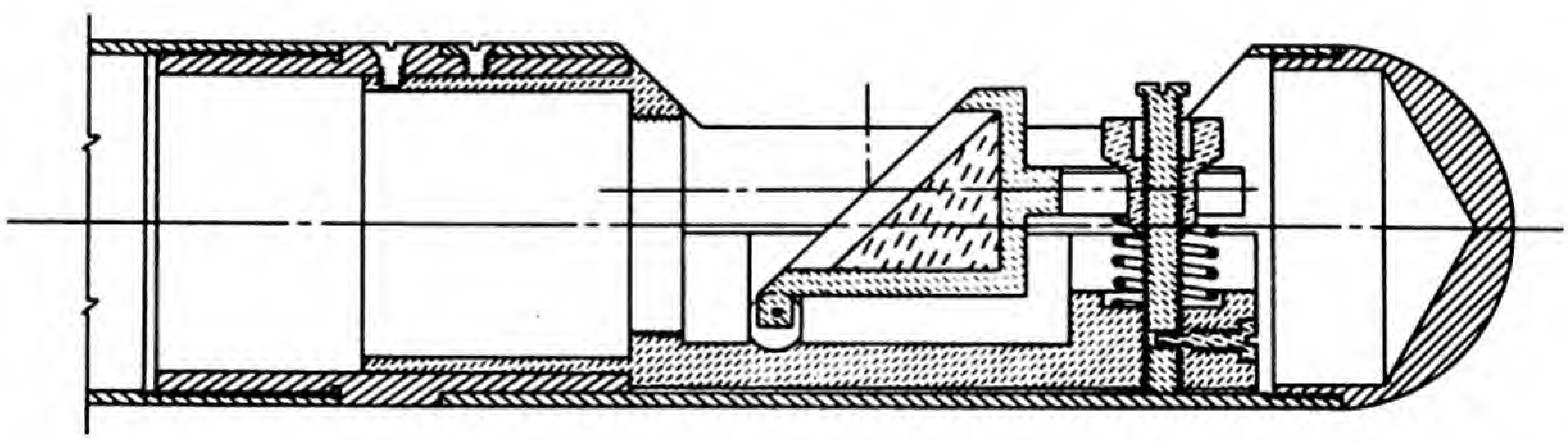


Fig. 1—Type D-B periscope head showing the adjustable mirror mount and threaded mount for the plastic objective-lens assembly.

signed. Conditions caused by the restricted operating space into which it was to be inserted and the need for close inspection of certain objects are met by the standard 4-ft borescope sections (see Paper 2.1). These sections, which allow easy assembling and dismantling, form the basic elements upon which the rest of the instrument is built. The head differs from that of the borescope by containing an adjustable scanning mirror (Fig. 1) and a short-focal-length objective-lens assembly and by omitting the electric lamp used in the borescope as a source of illumination. The eyepiece portion of the instrument (Fig. 2)

*This paper is based on Report CP-3120, Aug. 22, 1945.

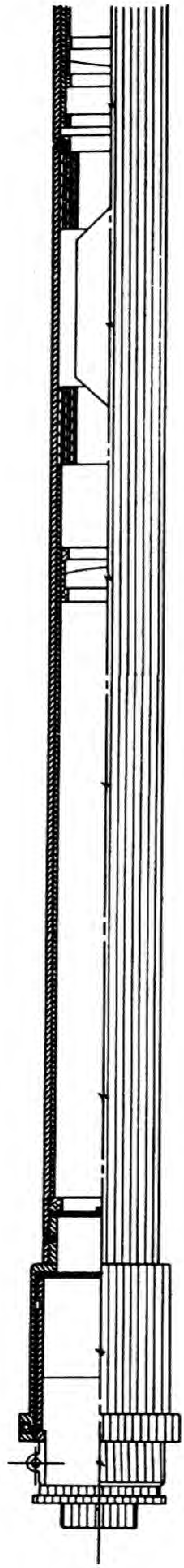


Fig. 2—Eyepiece section of type D-B periscope with Dove prism and focusing attachment.

differs in two respects from that of the borescope. Since the installation mountings are expected to provide sufficient shielding for the operators, the eyepiece section continues along the axis of the standard borescope sections to the observer's eye; it contains a Dove prism to give erect and normal-appearing images of the objects under inspection.

Paper 2.11

THE CHEMISCOPE*

By W. H. McCorkle

The chemiscope is a periscopic instrument of the borescope type designed for insertion into an enclosure through a 1-in.-diameter hole in a 2-ft-thick radiation shield. The length can vary from about 6 to 14 ft.

A rounded bullet-shaped tip carrying a small Stellite mirror and a standard plastic borescope objective, mounted in a piece of $^{15}/_{16}$-in.-diameter brass tubing about 14 in. long, constitute the scanning head of the instrument. Three different mirror-carrying tips may be provided, one for looking out of the side of the chemiscope tube perpendicular to its axis, one for looking forward approximately 45 deg from the perpendicular, and one for looking backward 45 deg from the perpendicular.

The head is attached to a 4-ft length of the tubing which contains two plastic borescope lenses turned down to such a diameter that they fit in the $^{15}/_{16}$-in. tubing. These lenses are arranged and spaced just as in the standard 4-ft borescope sections (see Paper 2.1). Additional 4-ft sections may be attached to serve as extenders. There are two types of eyepiece assemblies provided with the instrument. One (type A) resembles an auxiliary borescope crossarm in appearance, but focusing is accomplished by rotation of the eye-lens mount. The eye-lens mount has a spiral groove milled in its periphery, and a pin bearing in this causes the eye lens to move in or out of the eyepiece tube as the eye-lens mount is rotated. The crossarm has a slip-joint connection which permits rotation of the chemiscope tube while the crossarm remains motionless. Following the slip joint is a Stellite mirror which directs the light at right angles to the chemiscope tube

*This paper is based on Report CP-3117, Aug. 21, 1945.

into the side tube of the crossarm where it passes through two erecting lenses and then to another Stellite mirror which again deflects the light path 90 deg and directs it to the eye lens. Rotation of the eye-lens mount enables the observer to focus on objects at different

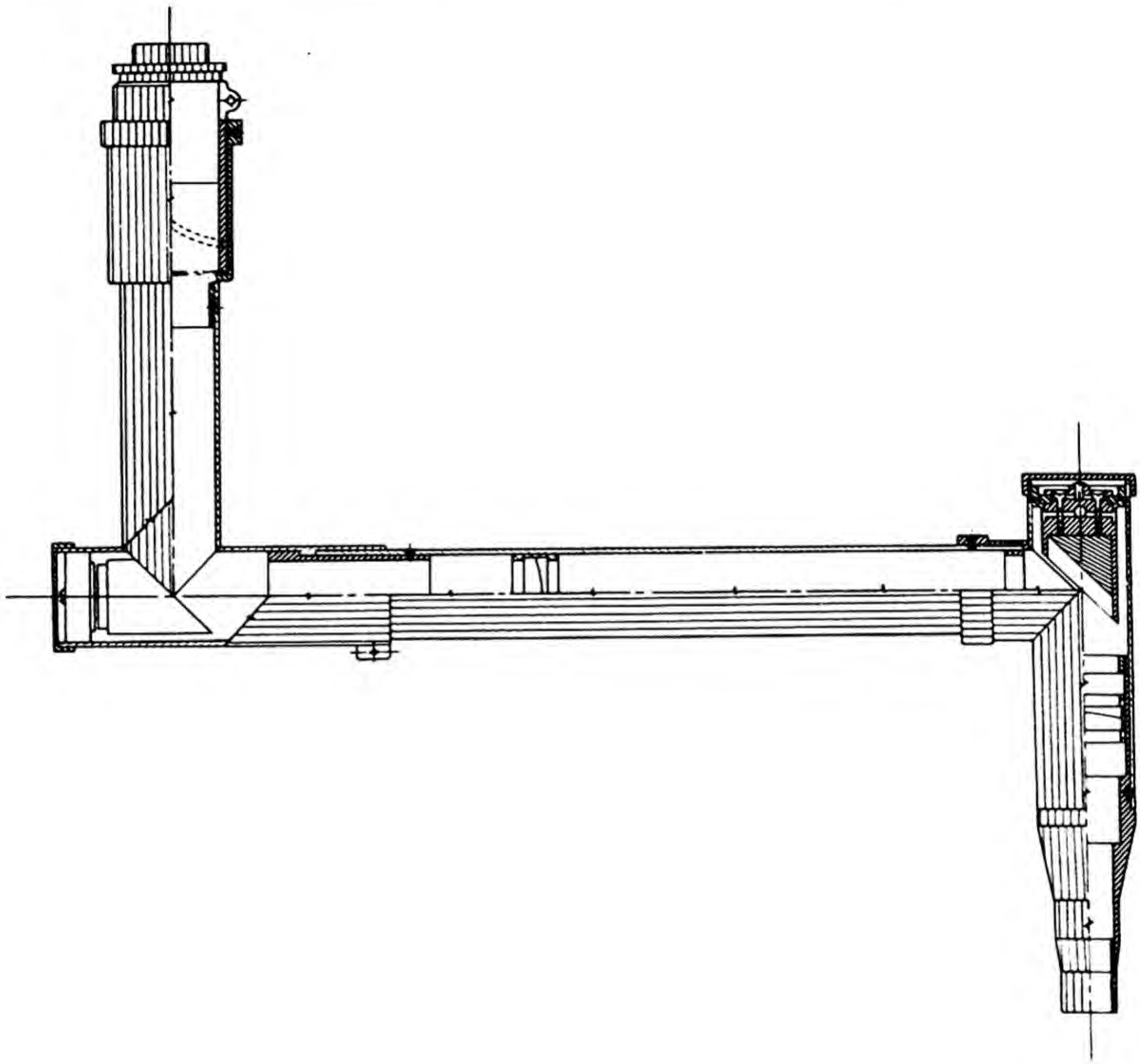


Fig. 1—Broken-away drawing of the chemiscope eyepiece assembly (type A).

distances from the scanning mirror. Features of the chemiscope eyepiece assembly are shown in Fig. 1.

The tubing of the second type of eyepiece assembly (type B) expands to approximately 1½ in. O.D. and carries a slip joint as in the type A assembly, but instead of having a crossarm attached it continues straight to the eye-lens mount. Following the slip joint the type B eyepiece assembly contains two achromatic plastic borescope lenses between which is mounted a Dove prism. Focusing for different ob-

ject distances is accomplished by rotation of the eye-lens mount just as with the crossarm type of assembly.

All exposed parts of the instrument are chromium-plated to reduce corrosion.

Paper 2.12

THE SHELFASCOPE*

By W. H. McCorkle

The shelfascope was designed and constructed to meet the need for a periscopic instrument to view changes accompanying certain chemical reactions. A sketch of the assembled instrument is shown in Fig. 1.

In use the objective tube is inserted through a hole in the radiation shield, and the mirror and eyepiece are adjusted in order that the above-mentioned changes may be observed.

The shelfascope consists of a Stellite mirror which is 2½ by ¾ in. and which is clipped to a mirror mount with a yoke attached and so arranged at the objective end of the instrument that the mirror can be rotated by means of a sheathed push wire W to direct light from the desired object into a Kellner-type Kollsman objective and thence to a Kollsman lens used as the first erector lens. A totally reflecting prism then directs the light through the second erector lens (Kollsman) to form an image in the focal plane of the adjustable eyepiece.

The slip joint at J allows rotation of the objective tube, and by means of the plunger P the push wire controls the mirror to include desired objects in the field of view.

*This paper is based on Report CP-3126, Aug. 22, 1945.

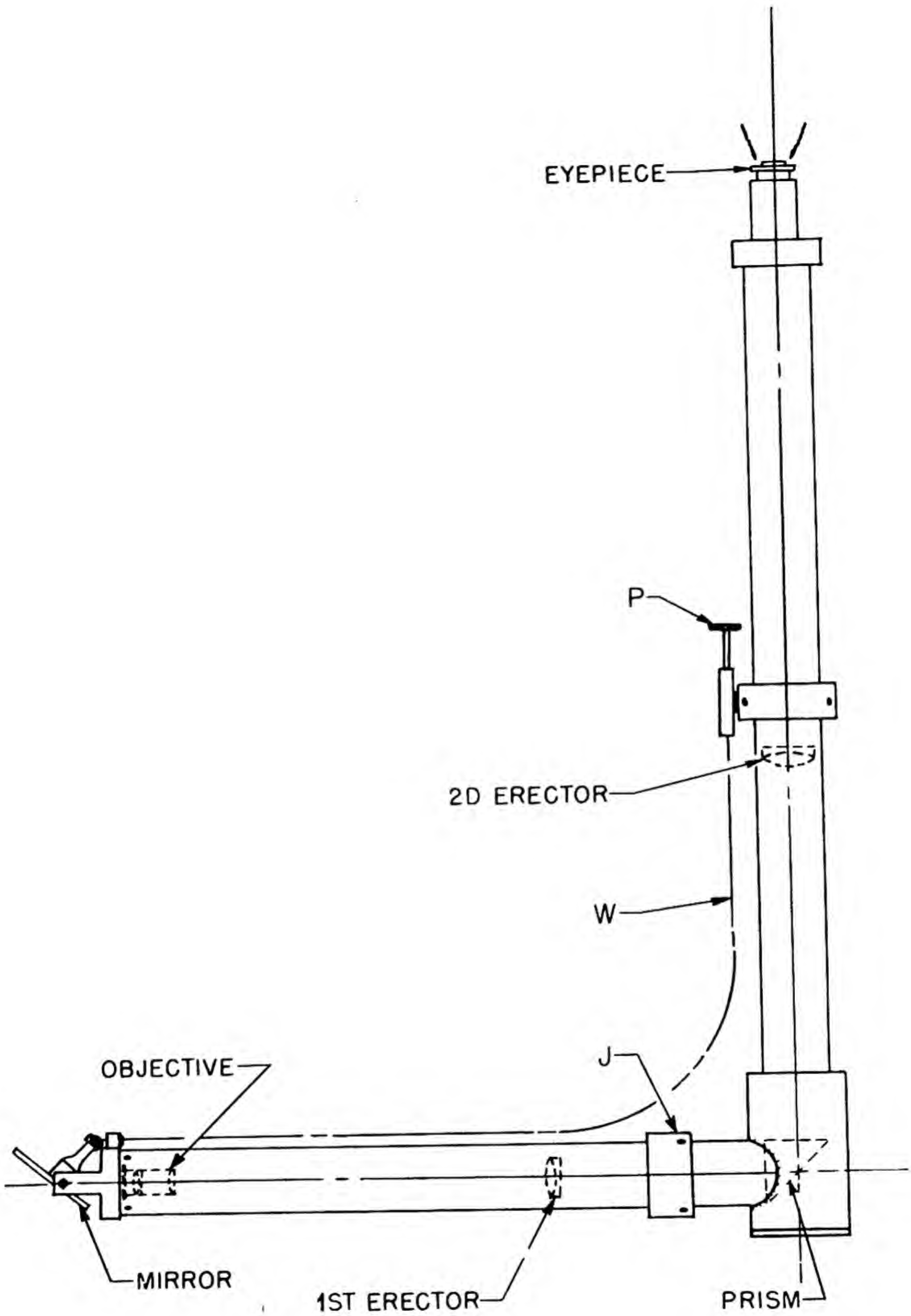


Fig. 1—Shelfascope with optical system indicated.

Paper 2.13

TYPE A-A PERISCOPE*

By W. H. McCorkle

1. INTRODUCTION

The type A-A periscope was designed and built to facilitate inspection, through rather small-diameter openings in the top of an enclosure, of vertical aluminum tubes in certain Project operations where corrosion might dangerously affect the outer surface of the tubes.

2. DESCRIPTION AND DETAILS OF INSTRUMENT

The requirements to be met were as follows: ability to focus on objects from a few inches to 2 or 3 ft distant from the scanning end, length adjustable from about 4 to 12 ft, diameter of 2 in. or less in order that openings already in the enclosure would be adequate, two directions of viewing the aluminum tubes (perpendicular and about 45 deg downward from perpendicular to the axis of the aluminum tubes), means for directing illumination of adjustable intensity on the surfaces being examined, and protection of the observer from the path of possible penetrating radiations.

All the above requirements were met by combining certain features of a borescope (see Paper 2.1) and the underwater bar viewer (see Paper 2.7) and by employing two special scanning heads for the instrument (see Figs. 1 and 2). The universal crossarm joined to three standard 4-ft borescope sections forms a periscope approximately 13 ft long. This may be used to focus on objects at a distance of from 6 to 8 in. from the open end of the borescope tube, but it is not usable for other object distances. In order to focus for a much greater range

* This paper is based on Report CP-3118, Aug. 21, 1945.

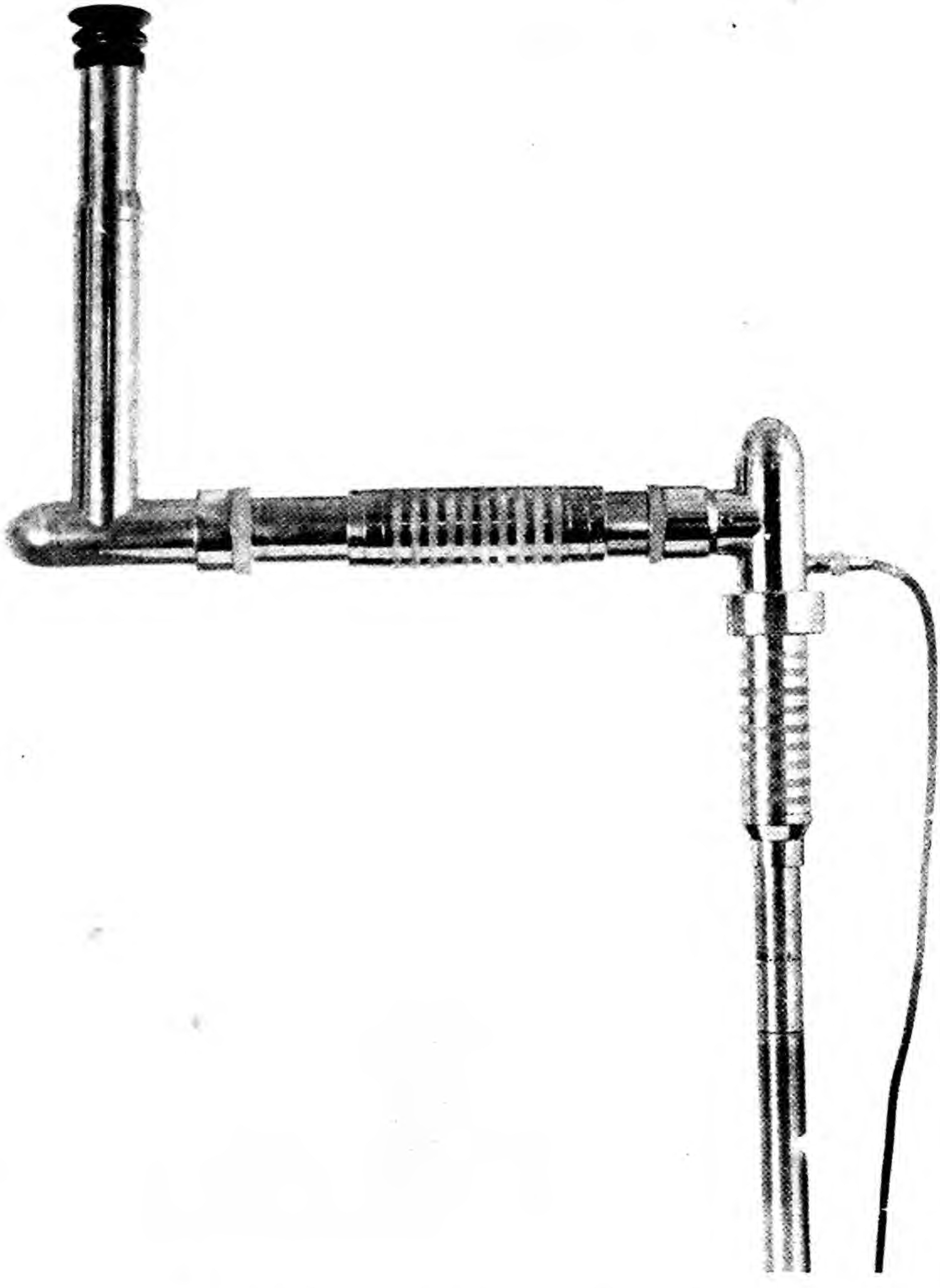


Fig. 1—Universal borescope crossarm.

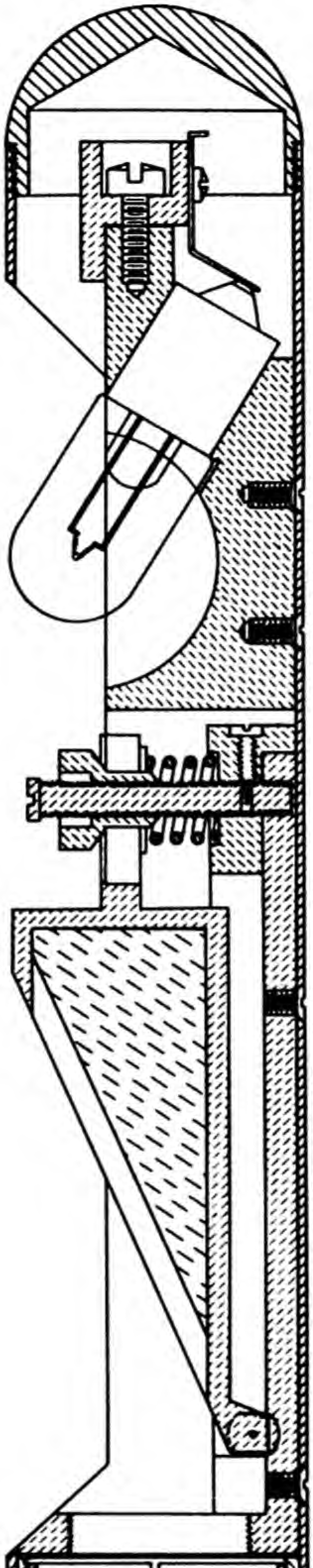


Fig. 2—Borescope head.

of object distances, a short-focal-length objective lens must be used as in the case of the underwater bar viewer. In the type A-A periscope, however, the objective needs to be coaxial with the borescope tube rather than perpendicular to it as in the underwater viewer. This head contains a short-focal-length Kollsman drift-sight objective, a 21-cp 6- to 8-volt incandescent lamp mounted in a special reflector socket, and a mirror (adjustable over a small angular range) for directing light from the illuminated object into the objective lens and then on through the borescope sections to form an image in the focal plane of the eyepiece, which is mounted in the universal crossarm. Mirrors can be so constructed that the view obtained is perpendicular to the axis of the borescope section or approximately 45 deg forward of the perpendicular direction. The two types of mirrors are interchangeable.

Paper 2.14

TYPE C-B PERISCOPE*

By George S. Monk and W. H. McCorkle

The type C-B periscope† was designed and constructed to give a larger field of view and greater magnification than was provided by the earlier periscopes developed for hot-laboratory use. Since this instrument has, in all cases at the time of writing, been constructed to replace another periscope, the length and diameter have been determined by the size of the original instrument.

The 706-CAX periscopes, for which type C-B periscopes have been substituted, used the Kollsman optical parts from a standard airplane drift sight which contained an objective assembly of rather small diameter. The diameter permissible for the C-B periscope tube, however, is sufficient so that by careful design of the device for operating the scanning mirror it is possible to use the same type large-aperture plastic triplet lens employed in the D-A periscope.[1] By combining this plastic triplet with a selected glass achromat of the proper large diameter, a very good wide-angle objective-lens assembly is formed. The size is such that it can be accommodated in a 3½-in.-O.D. tubing with a 1/16-in. wall, the largest permitted by provisions made for inserting the periscopes through the radiation shield. To maintain the large field of view, the first erector lens must be of larger diameter than that used in the airplane drift sight. The larger-diameter second erector of the drift sight is adequate for this application. Thus for the large field of view a symmetrical periscope was developed with the objective-lens assembly the same as the eyepiece assembly and with both erector lenses identical.

* This paper is based on Report CP-3127, Aug. 23, 1945.

† Known elsewhere as the "706-CBX periscope."

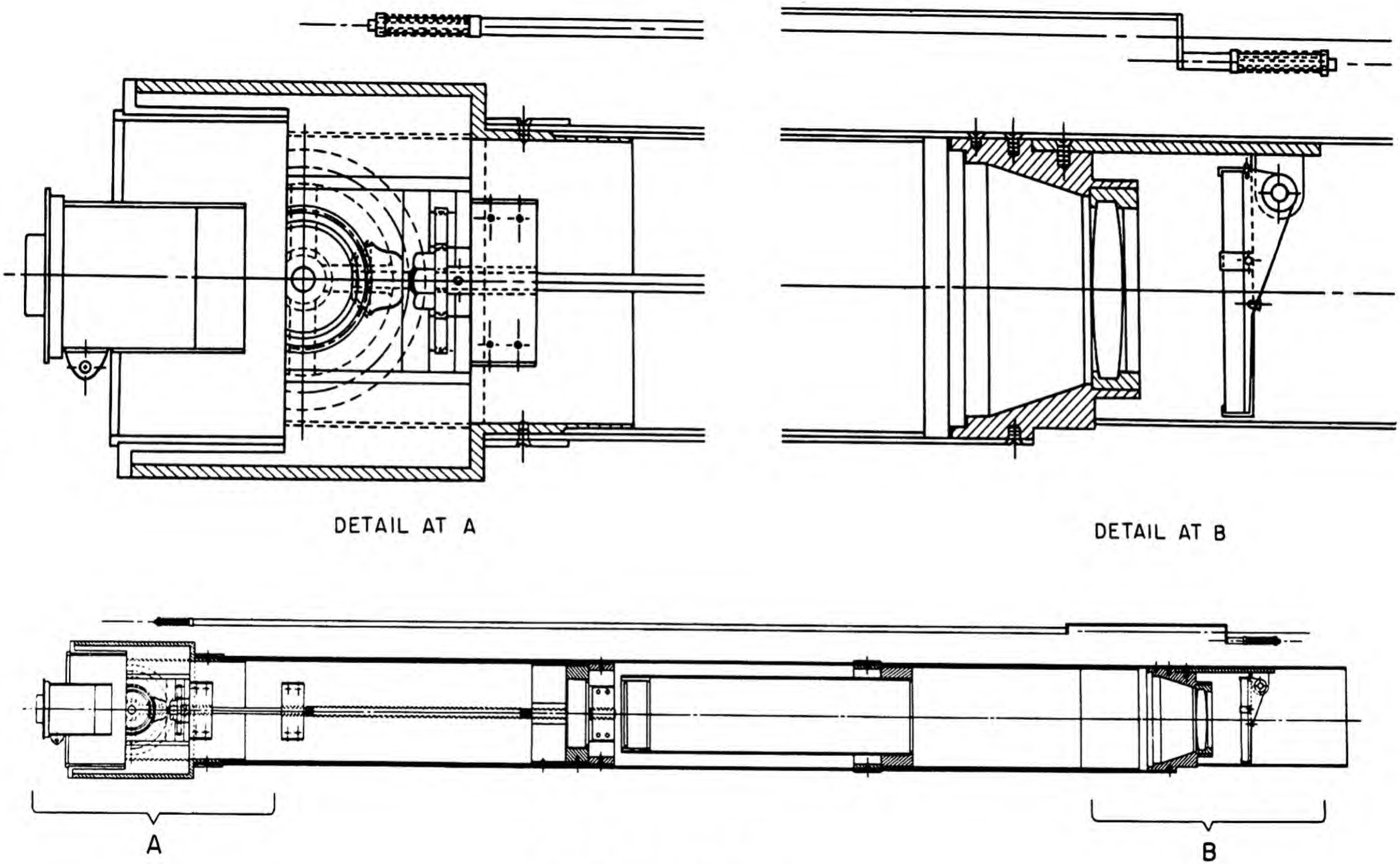


Fig. 1—Type C-B periscope.

To obtain higher magnification the combination plastic and glass eyepiece assembly is replaced by a Kollsman eyepiece of shorter focal length, and the second erector lens is moved closer to the eyepiece end of the instrument.

A screw and gear box device was developed to shift the second erector lens over the required distance of approximately 8 in. and also to control the focusing adjustment of the second erector lens. The features of the instrument are shown in Fig. 1, which was taken from the working drawing of the instrument.

REFERENCE

1. W. H. McCorkle, Report CP-3121, Aug. 22, 1945.

Paper 2.15

THE EXTENSOSCOPE*

By George S. Monk

1. INTRODUCTION

It was necessary to insert a periscope of variable length vertically through a hole 2 in. in diameter in the ceiling shield of a hot cell. It was to be used for viewing operations of equipment in the cell at levels ranging from 6 in. below the ceiling to 1 ft from the floor, a total vertical distance of 10½ ft. The objects to be viewed would be between 6 in. and 4 ft from the end of the periscope, in a horizontal direction. A magnification of unity or better was desired, and as large an angle of view as possible, consistent with the magnification and restricted diameter of the instrument, was needed. The possibilities of lens coloration were not excessive, and glass optical parts could be used.

The observer would be above the ceiling, and a horizontal eyepiece arm 4 ft above the floor of the concrete ceiling shield was desired. It was to be possible to scan the entire area of the hot cell at any level, but only a horizontal view was required. The observer should be free to manipulate control rods inserted through other holes in the ceiling.

2. CONSTRUCTION AND OPERATION OF INSTRUMENT

Several designs were considered. The one adopted is shown in Fig. 1. A sleeve is mounted in the 2-in. hole through the ceiling. Above this sleeve is a tubular housing 3½ in. in diameter and about 12 ft high. At its top is a large 45-deg prism, which directs light horizontally to another prism, by which it is directed downward into a second tube and thence horizontally to the eye.

* This paper is based on Report CP-3108, Aug. 10, 1945.

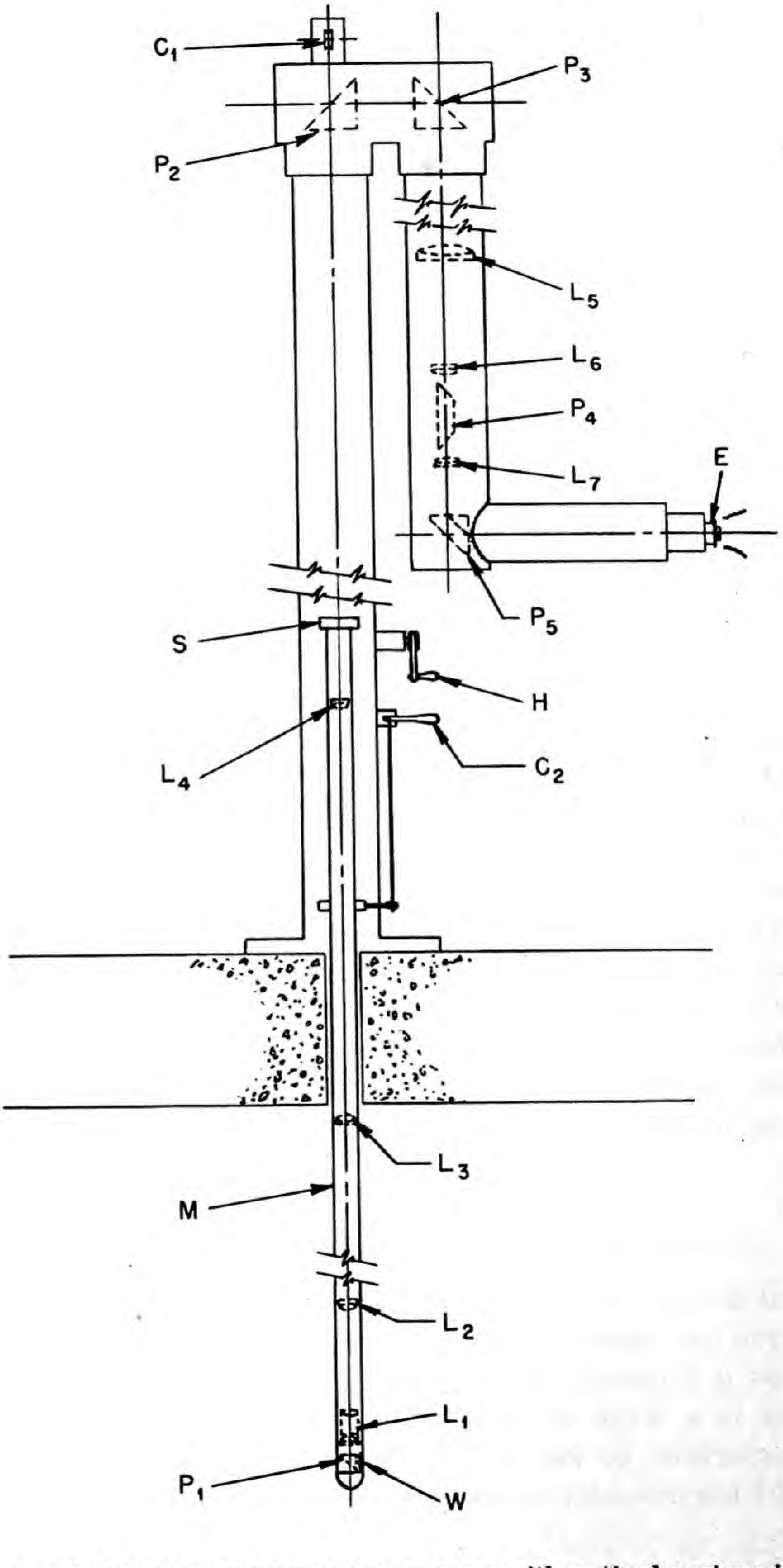


Fig. 1—Schematic diagram of the extensoscope with optical system indicated.

The scanning of the hot cell is done with a movable tube M, 1⅜ in. in diameter and about 13½ ft long. At the lower end of the tube is a 45-deg prism located at the entrance pupil of the system and followed by a Kellner-type Kollsman objective. The first erector lens and the two lenses following in train are all 1.25 in. in diameter and 24 in. in focal length. The beam of light issuing from the top of this narrow tube consists of parallel rays. Consequently, as the tube is elevated or lowered, no change of focal adjustment results. (Of course, a change in object distance still requires some focusing.) When this movable tube is at a given level, the entire space about its objective end can be scanned by rotating the tube about its axis. This is done by means of a clutch handle C_2. At the top of the tube is a slip ring S, which permits the tube to be turned freely without fouling the cable, which is fastened to the upper end of the tube and passes over the pulley system C_1 down to a control drum H.

If it is desired to scan at a different level, the tube M is moved up or down by means of H.

Rotation of M will cause the image to turn over. This can be compensated for by the following device: The parallel rays issuing from the top of M form a wide bundle, which is turned downward by the prisms P_2 and P_3 and received by the large lens L_5. Ordinarily this lens would converge the rays to an image at the focal plane of the eyepiece. To provide for re-erection of the image, the much-narrowed convergent bundle of rays is made parallel once more by lens L_6. Behind this is a Dove prism which can be turned about the optical axis to erect the image. The rays are converged once more to a focus and brought to a horizontal direction by the roof prism P_5.

Two eyepieces are furnished for variable magnification. With one of them, an object 24 in. away from the bottom end of the instrument is about one and a half times its size at arm's length. With the other, it is about twice as large.

The field of view is fairly constant and is about 13 deg. If at any time it is desired to increase the field of view, this can be done by replacing L_2 by a shorter-focus lens. However, this will be at the expense of magnification.

Focusing of the instrument can be done by moving the eyepiece. However, for near objects the range of motion will be large. To avoid this, provision is made for moving L_6 slightly up or down.

Paper 3.1

COLORATION OF A STANDARD PERISCOPE OBJECTIVE*

By George S. Monk

The periscopes made for hot cells are equipped with a standard drift-sight objective of the Kellner type. This contains an achromatic doublet of a dense barium crown-glass element and an extra-dense flint-glass element, with a field lens of borosilicate crown glass. Since two of these glasses were extremely darkened in the periscope in Building 105, it was decided to test the objective by irradiation even though the intensity at the hot laboratory is known to be far less than that at the Building 105 discharge area.

At Clinton Laboratories Henri A. Levy exposed an objective for 39 days to gamma radiation from two uranium slugs at an exposure intensity of about 20 r/hr. The total exposure was about 18,000 r and was in such a manner that all three kinds of glass were irradiated to the same degree. This exposure was approximately equivalent to more than two months of continuous direct exposure to the greatest activity that can be expected in routine operation of the cells. The lenses showed detectable although not severe darkening.

When the objective was taken apart and examined at Chicago, it was found that the borosilicate crown glass, which was darkened most in the discharge-area periscope, was not affected to any measurable degree in the test. The other two glasses were affected to approximately the degree that had been expected.

The over-all transmission of the objective was then measured. The transmission of the light diffusely reflected from a white matte surface was measured by P. R. Girardot with a Macbeth Illuminometer because other methods were temporarily unavailable. No compensation for color difference was found necessary. The eyepiece

*This paper is based on Report M-CP-1593, Apr. 21, 1944.

that was darkened by radiation transmitted 12.3 ft-candles, whereas an identical new eyepiece transmitted 14.1 ft-candles. (The reading with no eyepiece was 14.5 ft-candles.) An approximation of the percentage darkening gives $100(14.1 - 12.3)/14.1$ or 12.8 per cent reduction in the light transmitted. Allowing for error, 13 per cent will be an approximate value.

It is not certain whether there is much significance in the observation that the borosilicate crown glass was not colored so much as was expected. There have been, however, several isolated examples of similar discrepancies.

Paper 3.2

MISCELLANEOUS NOTES ON COLORATION OF OPTICAL MATERIALS*

By George S. Monk

1. COLORATION OF LITHIUM FLUORIDE

Samples of crystals of lithium fluoride made by The Harshaw Chemical Co. have been irradiated in a pile to determine the possibility of use of this material for optical purposes. The samples were about ¼ in. thick, split along cleavage planes, and not polished.

One piece (sample A) which was subjected to about 2500 kwh is ruby by transmission and dark green by reflection of daylight. Another piece (sample B), subjected to 1000 kwh, is dark orange by transmission and pale green by reflection of daylight.

The transmissions of samples A and B are shown in Fig. 1, on which the data are correct to about 5 per cent.

From these data it appears doubtful that lithium fluoride crystals can be used for optical purposes. Since, however, the coloration was produced by considerable amounts of neutron and gamma radiation, samples are being submitted, at the time of writing, to the Chemistry Division with a request that they be subjected to limited amounts of gamma radiation only.

2. COLORATION OF FLUORITE

Colorless fluorite from the Illinois field was placed in the Argonne pile and subjected to an irradiation estimated at 1200 kwh. It emerged a pale pink by transmission. The test was made to find its usefulness for optical purposes, in view of its advantage in correction of aberrations. Although the color was not deep enough to interfere with its usefulness, it is questionable whether its use is of much advantage because it is so hard to grind and polish in any size.

*This paper is based on Report CP-1687, May 11, 1944.

A point of interest is that the color of this sample is very much like that of a great deal of fluorite mined, whether from the Illinois fields or elsewhere. The decoloration (or curing) with time after being mined is well known. One deeply colored sample of Westmoreland fluorite, which came into the possession of the writer soon after being mined,

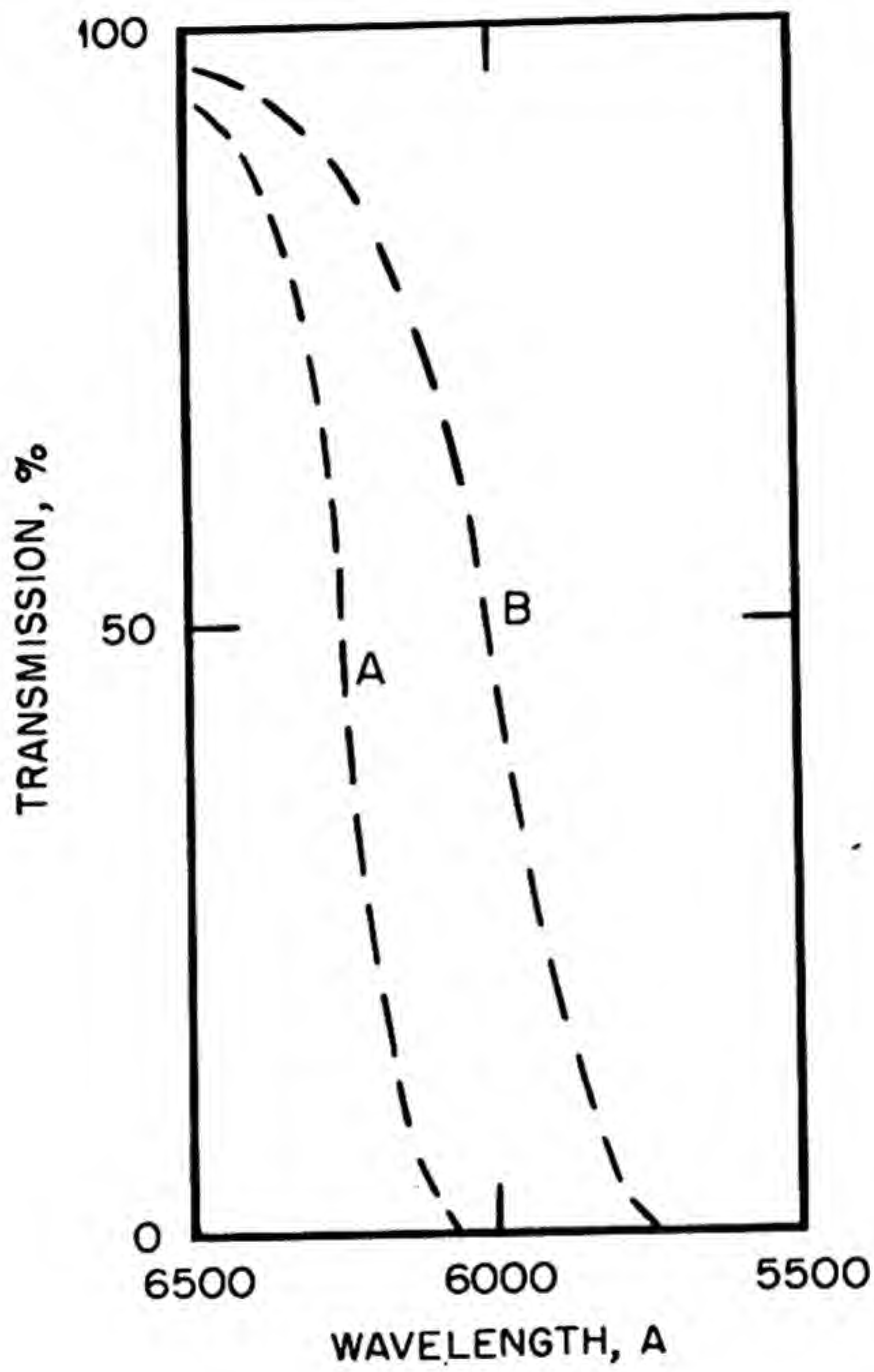


Fig. 1—Transmissions exhibited by two samples of lithium fluoride crystals.

is now clear of color for a depth of almost 1 cm. In the intervening time it has been resting on a shelf in a room with ordinary indoor lighting.

3. COLORATION OF GLASS AND PLASTIC SAMPLES IN A PILE

Some short sections of borescope tubing were placed in a shut-down pile, and in the tubing were loaded:

1. Borescope lenses made for a borescope
2. A Kellner objective of a standard periscope
3. An achromat of cyclohexyl methacrylate and styrene material planned for a borescope

The Kellner objective had been previously irradiated by Levy and was already slightly colored. It would have been better to use a new objective, but at the time there was none to spare.

The transmissions of all samples were measured by Girardot, and they are summarized in Table 1. In each case the colored samples were compared with new uncolored but otherwise identical samples.

Table 1—Effects of Radiation on Transmission

Time of radiation, hr	Transmitted ft-candles	Darkening achromat, %	Transmitted ft-candles	Darkening single lens, %
		Borescope Lenses		
0	9.6	0	9.6	0
1	9.5	1	9.5	1
2	9.3	3	9.3	2
		Kellner-type Objective Glass (Plastic Achromat)		
0	9.9	0	5.8	0
1		13*		
2	7.3	26	6.7	−15
16			5.7	2

*Previous irradiation.

It is difficult to interpret the value of −15 for the plastic achromat. At face value it means that the 2-hr irradiation improved the transmission 15 per cent, which the observers do not believe. Emphasis should be placed on the result of the 16-hr exposure. Here, too, it is questionable whether the 2 per cent represents a real lowering in transmission. Actually, the mean error with samples of plastics is close to 10 per cent, whereas that for the glass samples is nearly 3 per cent. This is partly due to the limited availability, at the time of writing, of plastic samples. The shape and size of the samples were not very suitable for photometric measurement. Additional tests of plastic lenses are planned.

The tests carried out during the limited time the pile was shut down indicate sufficiently well that the lenses now installed in the new 31-ft borescope should endure for the length of time that was anticipated when it was ordered. They indicate also that achromatic plastic lenses endure sufficiently longer to warrant their adoption for borescopes as soon as production of the required lenses begins.

Paper 3.3

COLORATION OF OPTICAL GLASSES*

By George S. Monk

1. COLORATION TESTS ON SAMPLES WITH DIFFERENT ANNEALING

Crystals can be made more subject to coloration by treatments such as sintering, sublimation, rapid recrystallizing, and deforming by pressure, which presumably increase the number of Schottky defects in the lattice. Anomalous coloring which was produced in different samples of boron-containing glasses, particularly borosilicate crown, in early experiments by the Optics Section was attributed to different annealing treatments. Accordingly, five samples of chemically identical borosilicate crown glass, each of which had received a different annealing treatment, were obtained from the Bureau of Standards. These samples were subjected to three different treatments in the region of a reactor:

1. One hour in the thermal column; flux, 5×10^{10} cm/sec
2. One hour in the thimble; flux, 10^{17} cm/sec
3. Sixteen hours in the thimble; flux, 10^{12} cm/sec

No difference in coloration between samples of the five glasses was detectable for any of the tests.

2. COMPARATIVE DATA ON COLORATION OF SELECTED OPTICAL GLASSES

Eleven different kinds of optical glasses were also obtained from the Bureau of Standards. (The compositions of the glasses are given in Table 1.) These included the types of glass mainly used in the manufacture of lenses, and many of which are incorporated in Project

* This paper is based on Report CC-3116, Aug. 21, 1946.

optical instruments. From these, pellets were cut and sent to the Argonne laboratory. They were irradiated for 1 hr in the thermal column of the CP-3 reactor operating at 300 watts. The flux was about

Table 1—Composition of Optical Glasses from Bureau of Standards

	Type of glass										
Sample No.	21	22	23	24	25	26	27	28	29	30	31
Designation	BSC	BaC	BaC	BaC	CF	F	F	F	F	BF	BF
(N-1)	517	541	6109	611	5281	572	5795	617	720	584	588
Dispersion No.	64.5	59.8	57.2	58.8	51.6	42.5	41.0	36.6	29.3	46.0	53.4
	Composition, %										
Silica (SiO_2)	66.4	58.8	38.25	38.3	65.4	55.1	53.1	45.6	34.1	49.8	45.8
Litharge (PbO)			0.2	0.2	10.0	31.7	35.5	43.1	62.4	18.8	10.0
Barium oxide (BaO)		19.9	42.85	42.8	0.2	1.0	0.5			13.4	25.9
Calcium oxide (CaO)			2.3	4.5							
Alumina (Al_2O_3)			4.9	2.9							
Zirconia (ZrO_2)											1.5
Zinc oxide (ZnO)	0.5	4.1	4.2		3.6					7.8	
Soda (Na_2O)	8.2	3.2			13.2	5.0	0.4	4.7		1.5	0.8
Potash (K_2O)	12.0	10.3			5.6	6.9	9.7	6.1	3.2	8.2	6.7
Arsenic oxide (As_2O_3)	0.5	0.3	0.4	0.4	0.2	0.3	0.3	0.5	0.3	0.5	0.5
Antimony oxide (Sb_2O_3)			0.2	0.2	1.8		0.5				
Boric oxide (B_2O_3)	12.4	3.4	6.7	10.7							8.8
Est. transmission, %	4	7	12	6	96	85	90	87	87	82	8

21 22 23 24 25 26 27 28 29 30 31

Fig. 1—Optical glasses after irradiation at the Argonne laboratory (see Table 1). Sample 21, dark brown; sample 22, smoke; sample 23, dark yellow brown; sample 24, smoke; sample 25, white; sample 26, yellow; sample 27, yellow white; sample 28, yellow; sample 29, pink white; sample 30, yellow; sample 31, dark yellow.

5×10^{10} cm/sec. The results are shown in Fig. 1. There was insufficient time for a rigorous photometric analysis which would have made it possible to prepare empirical formulas for composition for new glasses which would give minimal coloration.

Experiments on bleaching of these glasses were inconclusive. More work is necessary to determine whether bleaching would be expedient.

3. CALCULATION OF ACHROMATS FROM THE MOST RESISTANT GLASSES

Attention is called to the exceedingly small amount of coloration of the following samples (see Table 1):

1. No. 25: index of refraction, 1.529; dispersion No., 51.6; CF_1
2. No. 27: index of refraction, 1.5795; dispersion No., 41.0; LF_2
3. No. 29: index of refraction, 1.720; dispersion No., 29.3; EDF_3

The first of these is crown flint glass, which is not used a great deal for achromatizing lenses. The second is a light flint and the third

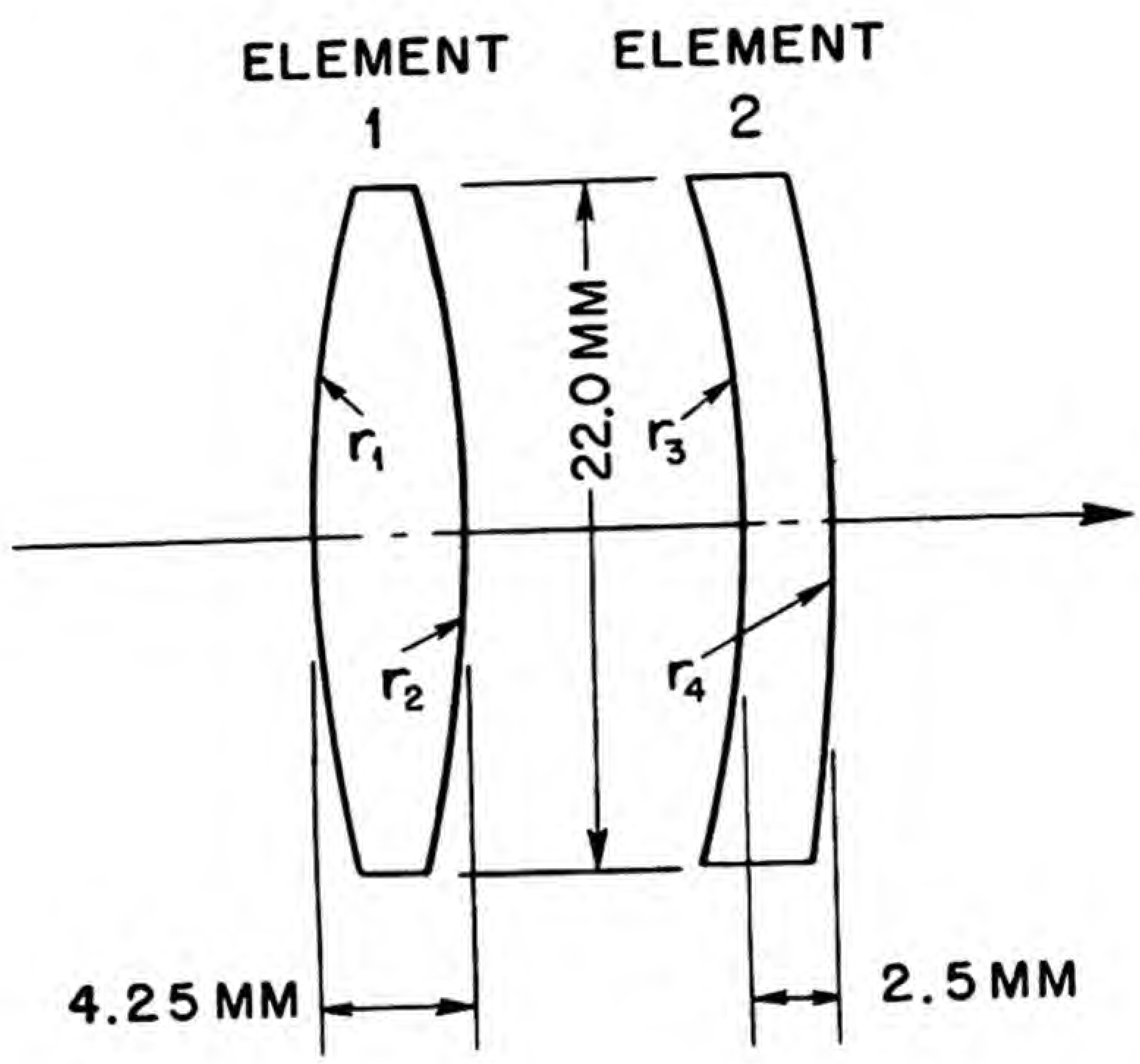


Fig. 2—Lens system recommended for minimum coloration; object at infinity; effective focal length, 100 mm; cemented doublet.

is a dense flint. Walter Wallin calculated achromats, using combinations of 1 and 2 and 1 and 3. The ratio of 5 to 1 was chosen for the ratio of focal length to linear aperture, since that would be a suitable figure for a short-focus achromat to be used as the objective of a periscope. This element of the periscope was chosen for examination because it is the one most likely to be exposed to high-energy radiation.

Wallin reported as follows: "neither the combination CF_1 and LF_2 nor the combination CF_1 and EDF_3 gives exactly ideal optical results. For a combination of CF_1 and LF_2 the indices and dispersions are so

close that very steep curves are necessary for achromatism at the axis. Then, when spherical aberration is corrected for any height above the axis, the residual spherical aberration at other heights is much greater than for other combinations."

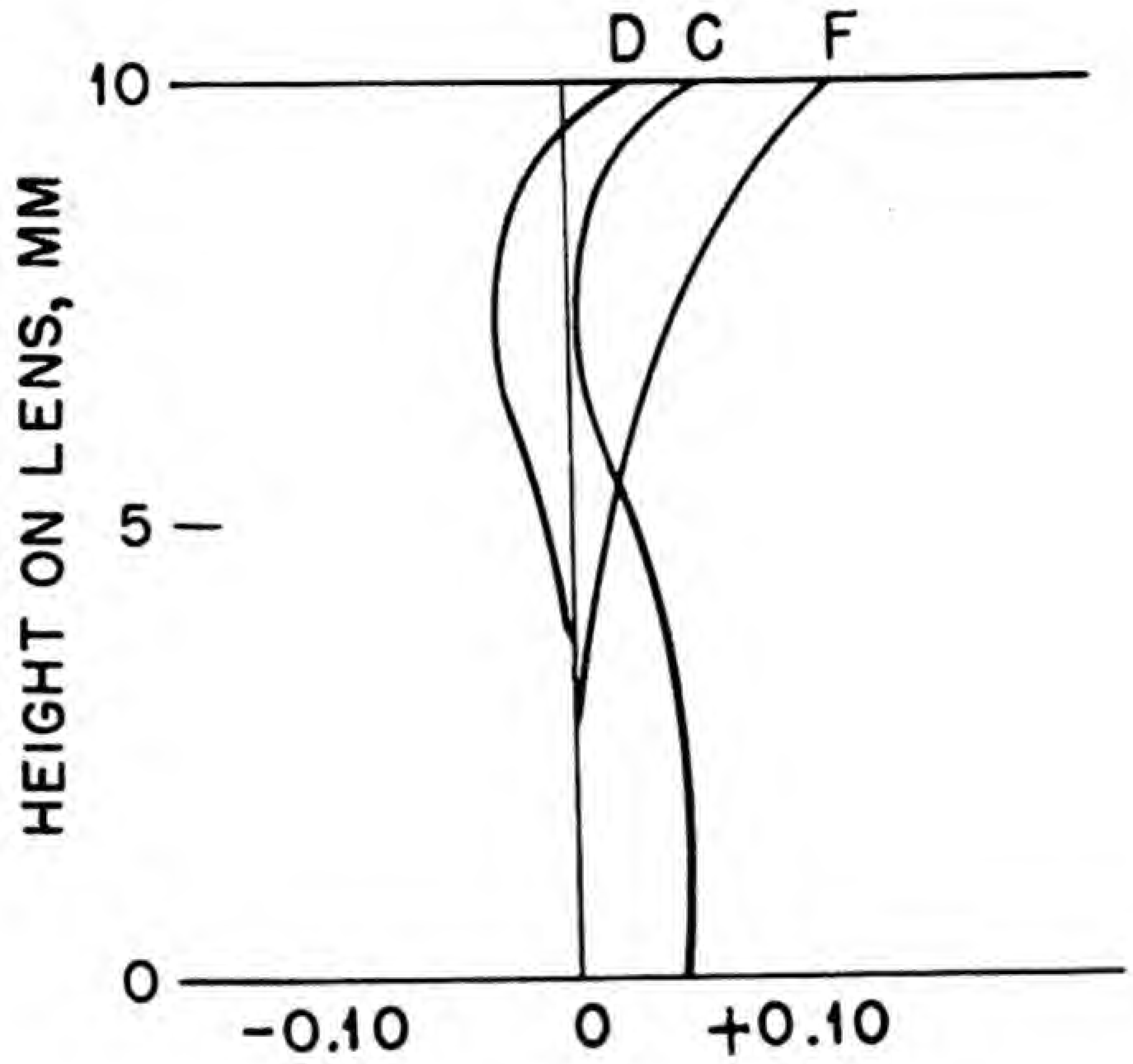


Fig. 3—Longitudinal spherical aberration and color of optical glass as a function of the height of point on lens; paraxial D-line focus taken as origin.

Although no calculations were made, there is a distinct possibility that a combination of LF_2 and EDF_3 might turn out well. Although the LF_2 and EDF_3 combination might be optically useful, the coloration would be greater than desirable. The only glass which is highly resistant to coloration is crown flint.

The specifications for the lens selected as the most desirable are as follows (see Figs. 2 and 3): Element 1, CF_1 glass; n_D, 1.5286; V, 51.6. Element 2, EDF_3 glass; n_D, 1.7200; V, 29.3; r_1, 40.35 mm; r_2, 49.94 mm; r_3, 49.94 mm; r_4, 1253.5 mm. Recommended design: coma; 2 per cent with entrance pupil at objective.

Paper 4.1

THE CASE FOR PLASTIC LENSES*

By George S. Monk

At the time the original report was written, the use of plastic lenses seemed to be the only immediate practical solution of the radiation problem[1,2] involved in the construction of periscopic instruments (see Paper 4.2). There has not yet been found any feasible design in which large numbers of mirrors can be substituted for lenses. The best aluminum mirrors rarely have a reflectance higher than 90 per cent for the visible spectrum, whereas Stellite and other durable and noncorrosive alloys average about 80 per cent. In comparison, the transmission of a coated lens is 97 per cent or better. Then, to avoid oblique aberrations, the mirror system must be centered, resulting in restriction on the aperture and consequent danger of diffraction, as well as light loss. If there were sufficient time, it is probable that uncentered mirror systems could be built, which would afford freedom from oblique aberrations and diffraction; however, these are now only optical curiosities, and the quantity production is not possible at the time of writing. It is obvious that the situation requires full utilization of the presently developed plastic lenses.

An investigation was begun on Lucite as an optical material. This was not promising, and early in 1944 it was disclosed[3] that Sec. 16.1 of the National Defense Research Committee (NDRC) had perfected the manufacture of achromatic lens systems by combining lens elements made of two plastics, cyclohexyl methacrylate and styrene. The lenses are molded in pyrex molds. These two plastics are fitted for use in optics because of their resistance to water and their relatively high melting point. A good durable low-reflection coating can be put on them, and they are relatively inexpensive in large quanti-

* This paper is based on Report M-CP-1681, May 6, 1944.

ties. Arrangements were made to use these materials and adapt, if possible, any lenses already designed.

Plastics are not completely satisfactory substitutes for glass. Although their transparency is high, they scatter light more than glass; thus with a considerable thickness of material the contrast is diminished seriously. Also, they scratch easily and are difficult to grind and polish. Although there is an abundance of good optical glasses with sufficient variety of indices of refraction and dispersions for corrections of aberrations, only two good plastics are thus far available. It is reasonably certain that the development of newer optical plastics will be achieved even with the use of materials more subject to coloration than are the two now used.

An investigation was made of the relative resistance of plastic and glass lenses to coloration. Beginning in August 1943 (before the use of cyclohexyl methacrylate and styrene), six pieces of Lucite, numbered 1 to 6, were placed in a pile[4] (see also Paper 3.2). With them were placed six pieces of light barium crown glass, similarly numbered. The samples numbered 1 were withdrawn from the pile after an estimated 60 kwh. The others were withdrawn successively after greater amounts of exposure, until No. 5 had about 1500 kwh. Whereas glasses 3, 4, and 5 were all very dark (a 1-in. thickness being opaque for ordinary brightness), the Lucite pieces 3, 4, and 5 were only slightly yellow, with little or no increase in yellowing of 5 over 3. The samples numbered 6 were left in the pile about 10 weeks. In this case, the Lucite was colored slightly more than the other samples and to an extent that would render it of dubious value optically.

Since Lucite is a methacrylate, it was expected that cyclohexyl methacrylate would react similarly, and this was found to be the case. As soon as specimens of lenses developed by NDRC were received, samples were submitted to the Chemistry Division, where they were submitted to a gamma irradiation of 10^6 r. The cyclohexyl methacrylate was very slightly yellowed, but the styrene was not appreciably yellowed. Subsequently, several samples of cyclohexyl methacrylate and styrene were inserted into the pile and withdrawn after being given estimated amounts of irradiation. A pair which was withdrawn after about 2400 kwh showed precisely the same degree of effect as those irradiated with 10^6 r of gamma rays.

What seems to be a marked divergence from the high resistance to radiation shown by styrene occurred in the case of the samples left in a pile for 10 days, during which the pile developed 6.8 megawatt-days. Whereas the cyclohexyl methacrylate was only slightly yellow, the styrene was amber colored. Subsequent to its removal from the pile it showed evidence of curing, that is, its coloration reduced, through-

out a zone beginning at the outer surfaces. Since heat appeared to accelerate the curing of glasses, one piece of styrene was heated, with no result that could be observed. The curing observed has proceeded at a rate apparently unchanged by external operations. It should be emphasized that this curing was not a complete disappearance of color but simply a change from a dark yellow brown to a clearer amber. At any time in the process, the outline of the uncured portion was very sharp. This gradual curing with time, also very marked in glasses and colored crystals, has not been observed in any other plastic samples. Too much should not be inferred from this isolated observation on one sample of styrene. Other factors, such as temperature and the relative effects of neutrons and gammas, were not under control. Controlled experiments that will give more information on this point are in progress. However, it is certainly not planned to use borescopes in the pile during operation. For instance, the borescope for Hanford will be designed for use while water is flowing at a reduced rate through the tube to be examined and while the temperature is well below the danger point. Also, in all cases where periscopes must be left in the discharge areas, the Chicago Optics Section incorporates a device for moving the exposed lenses to a screened position, except when they are actually being looked through.

Later calculations by Way[5] have indicated that the life of a borescope will be too short for successful use. To check this, some lengths of borescope tubing loaded with glass and plastic samples were tested. After 2 hr in the shut-down pile, the glass samples showed little or no coloration and that only in the case of borosilicate crown, which has already been earmarked for avoidance. The plastic samples showed no effects whatever. Exposures for longer periods are in progress at the time of writing, but it is not expected that they will add material information to the results of the long-time exposures already obtained.

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2. W. L. Kay, Report CC-841, Aug. 7, 1943.
3. George S. Monk, Report MUC-GSM-80, Apr. 11, 1944.
4. R. A. Day and G. Jenks, Report CC-1109, Dec. 11, 1943.
5. Katherine Way, Report MUC-KW-6, Apr. 17, 1944.

Paper 4.2

AN ALL-PLASTIC OPTICAL SYSTEM FOR PROJECT PURPOSES*

By George S. Monk

Tests have shown that the lifetime of the plastic achromatic lens, a combination of a methacrylate positive element and a styrene negative element, would be 100 to 1000 times as great as that of glass lenses in the presence of the same quantities and kinds of radiation. Several different optical systems have been developed. With the use of one or two additional plastic lenses, which are under design by the Optics Section at the time of writing, other geometrical systems are possible. Still others of high correction in color and geometrical aberrations are possible by combining these plastic lenses with glass achromats, the latter being placed in such positions in the system that they are protected from radiation. All lenses may be mounted in plastic tubes.

The optical characteristics of plastic lenses are interesting. If an achromat of about 15-in. focal length and 3-in. diameter is combined with a Kellner-type eyepiece of about 6-in. focal length and the same diameter, the exit pupil is about 1 in. in diameter and 6 in. from the emergent face of the eyepiece. Thus the instrument is easy to look through and allows considerable freedom of head position. Since the exit and entrance pupils are the same size when these lenses are used symmetrically in periscopes, there is no loss of light occasioned by the large exit-pupil diameter.

It is now possible to use plastic optical systems for most Project purposes. Among the instrument designs affected are:

1. Periscopes through biological shields about piles
2. Periscopes into other pile areas
3. Periscopes into separation cells

*This paper is based on Report M-CP-1680, May 6, 1944.

4. Periscopes into hot laboratories
5. Periscopes into centrifuges
6. Borescopes for examination of interiors of pile tubing
7. Underwater periscopes

In some cases the lenses exposed to direct radiation may be retracted as much as 6 ft, thus moving them far back into the radiation shield. Simple mechanical devices may then be arranged to move a shielding block in front of the lenses. The net result will be to make it unnecessary to take a periscope out of the hole through the shield.

Paper 4.3

A NEW WIDE-ANGLE ALL-PLASTIC PERISCOPE*

By George S. Monk

The acquisition of new plastic-lens designs has enabled the Optics Section to exceed the usual limitations on the angle of view and magnification of the periscope. One was constructed which was no more than 3½ to 4 in. in diameter and 36 in. or more in length. This periscope has an angle of view of 60 to 65 deg, which compares favorably with such over-all viewer installations as those made in hot laboratories. For relatively near objects the magnification of this periscope is approximately unity.

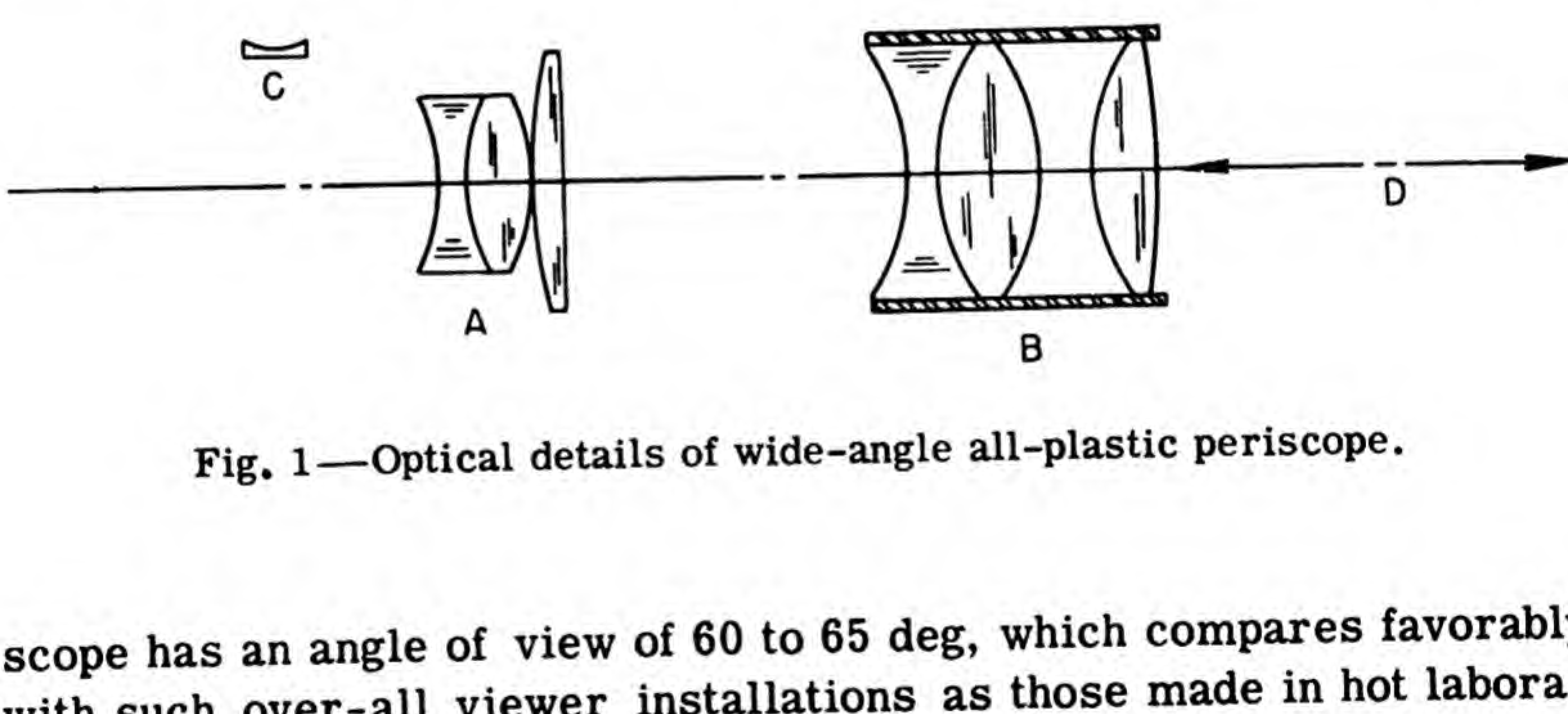

Fig. 1—Optical details of wide-angle all-plastic periscope.

A laboratory model 8 ft long and 2½ in. in diameter has an angle of view of 64 deg. When the objective magnifier is adapted to this instrument, the magnification is increased to over 4 for an object 10 ft away. Thus it is possible to read four-point type with ease. Figure 1 shows the optical details of the instrument.

A feature of this new periscope is that most of the lens elements of the objective magnifier constitute part of the periscope objective it-

* This paper is based on Report MUC-GSM-166, Nov. 14, 1944.

Table 1 — Comparison of Optical Characteristics of Five Instruments Commonly Used on the Project

Optical property	Tank over-all viewer	Telescope	4-element sight periscope	Borescope-type periscope	New wide-angle periscope
Angle of view					
Without objective magnifier, deg	45–110	Small	5–30	5–24	Up to 65
With objective magnifier, deg	?	?	Reduced	?	Up to 20
Limits of length of entire instrument, in.	30–90	Any length	30–150	Up to 500	35–100
Range of possible diameters, in.	8–30	Any	1–4	1–4	4
Size of entrance pupil, in.	Eye	Objective	0.4–0.8	0.4	0.4–0.8
Size of exit pupil, in.	?	0.1–0.4	0.3–0.8	0.3–0.4	0.7–1.0
Distance of entrance pupil from objective, in.	?	Objective	1.0–5.0	1.0	0.3–8.0
Distance of exit pupil from ocular, in.	?	0.2–0.5	0.4–0.6	0.4–0.6	4.5–7.0
Adaptability of objective magnifier	None	Unnecessary	Yes	None	Excellent
Scanning mirrors or prisms	Dubious	Good	Good	Good	Fair
Probable light transmission, %	50–75	60–80	40–65	20–35	35–65
Magnification					
Without objective magnifier	Small	1–20	1–4	0.5–1	0.6–1.25
With objective magnifier	?	?	8–40	?	3–6

self. Figure 2 shows that these elements may be inverted in position by a simple mechanical control to form part of the magnifier which gives higher magnification.

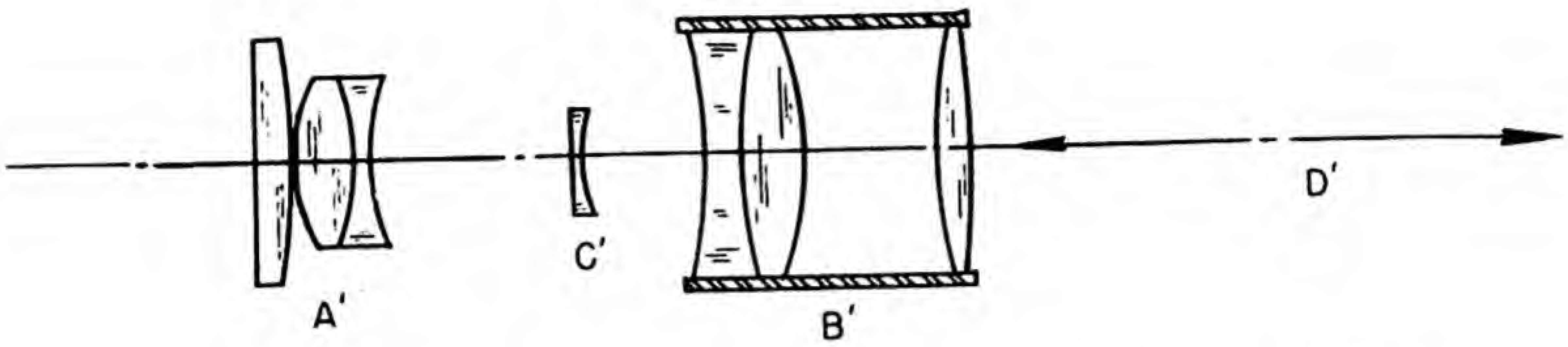

Fig. 2—Objective magnifier arranged to give high magnification.

Table 1 is a comparison of the optical characteristics of the over-all viewer, an ordinary telescope, a four-element "sight" periscope, a borescope-type periscope, and the new wide-angle all-plastic periscope.

Paper 4.4

SCRATCH RESISTANCE OF PLASTIC OPTICAL MATERIALS*

By K. F. Whitcomb

ABSTRACT

Tests were made of the scratch-resistance or hardness values of glass and various plastics by the mar-resistance method, the brush surface-analyzer method, and the Shore scleroscope method. By all three methods scratch-resistant Lucite was found to be the most scratch resistant of the materials tried, and soft methyl methacrylate was more scratch resistant than styrene.

1. INTRODUCTION

Rapid darkening of the glass lenses built into the optical equipment used on this Project has led to the use of plastic lenses and windows which are acted on by penetrating radiations much less than glass.

One of the main objections to plastic lenses on this Project is the fact that they are softer than glass, and as a result they are apt to be scratched while the optical equipment is being built.

The object of this investigation was to compare the scratch-resistance or hardness values of the following plastics with lantern-slide cover glass using a standard American Society for Testing Materials (ASTM) scratch-resistance test and also to devise more suitable tests:

1. Scratch-resistant Lucite, No. 674-166-1 (SRL)
2. Soft methyl methacrylate (SMM)
3. HC201 Lucite (HC201)
4. Cyclohexyl methacrylate (CHM)
5. Styrene
6. Polystyrene (PS)

*This paper is based on Report CP-2266, Oct. 23, 1944.

2. INVESTIGATION

2.1 Mar-resistance Method. The first method of test used in measuring the scratch resistance of these plastics was one recommended by ASTM, "Mar Resistance of Plastics," D673-42T. This method involves the measuring of the gloss from a surface scratched by abrasive falling on it. The results obtained with this test are given in Table 1.

Table 1—Hardness Determined by Mar-resistance Method

Run	Material tested	Type of reflected light*	Exposed meter reading: Polished surface	Exposed meter reading: Abraded surface	I_1/I_3, % specular light†	$\frac{I_1 - I_2}{I_1}$, % gloss	Hardness, % original gloss
6	Glass	Specular	$I_3 = 8$	$I_1 = 7\frac{3}{4}$	97		
			$8\frac{3}{8}$	$8\frac{1}{8}$		11.8	51.5
		Diffused	$I_2 = ?$	$I_2 = 7$			
10	Glass	Specular	$I_3 = 7$	$I_1 = 6\frac{3}{4}$	96.5	11.1	48.5
		Diffused		$I_2 = 6$			
2	SRL	Specular	$I_3 = 7\frac{3}{4}$	$I_1 = 7\frac{3}{8}$	95.4	22	96
		Diffused		$I_2 = 5\frac{3}{4}$			
9	SRL	Specular	$I_3 = 7\frac{3}{4}$	$I_1 = 7\frac{1}{4}$	95.0		
				$7\frac{1}{2}$			
		Diffused		$I_2 = 6$		18.7	81.6
3	CHM, convex	Specular	$I_3 = 7\frac{1}{4}$	$I_1 = 6\frac{3}{4}$	93		
5	Styrene, convex	Specular	$I_3 = 7\frac{1}{2}$	$I_1 = 6\frac{3}{4}$	90	3.7	16.2
		Diffused		$I_2 = 6\frac{1}{2}$			
7	HC201	Specular	$I_3 = 8$	$I_1 = 7$	86		
			$7\frac{3}{4}$	$6\frac{3}{4}$			
				7			
		Diffused	$8\frac{1}{4}$	$I_2 = 6\frac{1}{2}$		5.4	23.8
8	HC201	Specular	$I_3 = 8\frac{3}{4}$	$I_1 = 7$	80	3.6	15.7
		Diffused	$I_2 = 6\frac{3}{4}$	$I_2 = 6\frac{3}{4}$		22.9	
1	SMM	Specular	$I_3 = 7\frac{3}{4}$	$I_1 = 6$	77.5	4.2	18.3
		Diffused		$I_2 = 5\frac{3}{4}$			
4	SMM	Specular	$I_3 = 7\frac{3}{4}$	$I_1 = 6\frac{1}{2}$	83.9		
		Diffused		$I_2 = 6$		7.7	33.6

*Exposure-meter angle: specular, 45 deg; diffused, 45 to 60 deg.
†Reflected.

The abrader is shown in Fig. 1. Abrasive is dropped through a vertically supported brass tube A, 24 in. long and $\frac{3}{4}$ in. I.D., onto the test specimen C, which is supported at an angle of 45 deg. From a

beaker, 400 g of 80B Crystolon abrasive is poured into a glass funnel B in 2 min. The beaker is rotated in a circle (using a uniform rate) with the radius equal to EF in order that the abrasive, when dropped

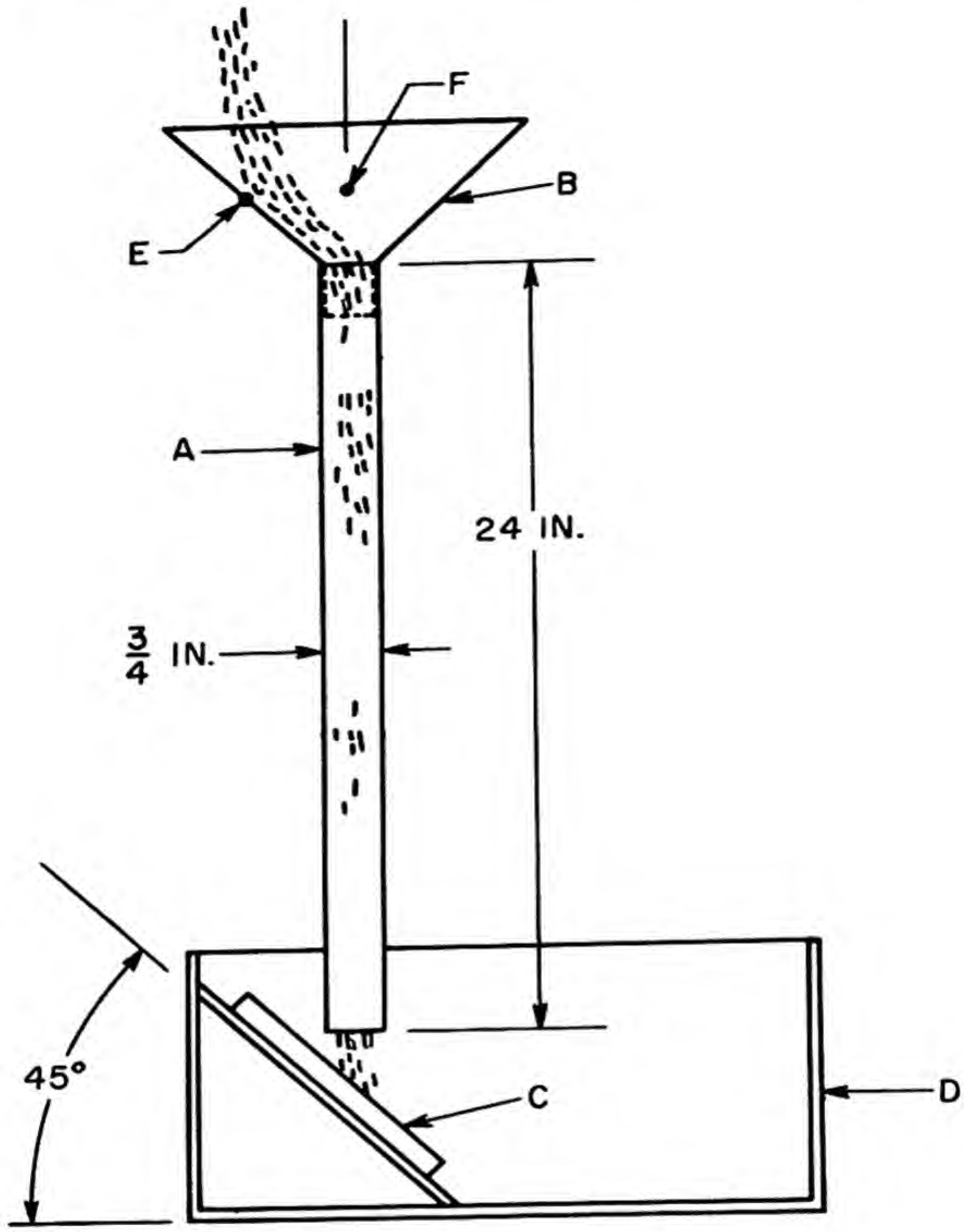

Fig. 1—Abrader.

from the beaker, will hit at a distance EF from the center line of the tube. A box D catches the abrasive after it has fallen on the specimen C.

The glossmeter is shown in Fig. 2. The projector A contains a 50-cp 8-volt electric bulb, the light from which passes through a condensing lens D and a $^{15}/_{16}$-in.-diameter diaphragm to a specimen C. Light from A is projected onto the scratched surface of specimen C at an angle of 45 deg. A General Motors exposure meter B is directed at surface C at an angle of 45 deg. The exposure meter in this position is used to measure the specular light reflected from surface C.

Exposure meter B is moved to a new position and so directed as to form an angle of 60 deg with specimen C. In this position the exposure meter reads the diffused light which comes from the scratched surface C. A piece of white paper E is placed between specimen C and the table as a white background for the meter reading.

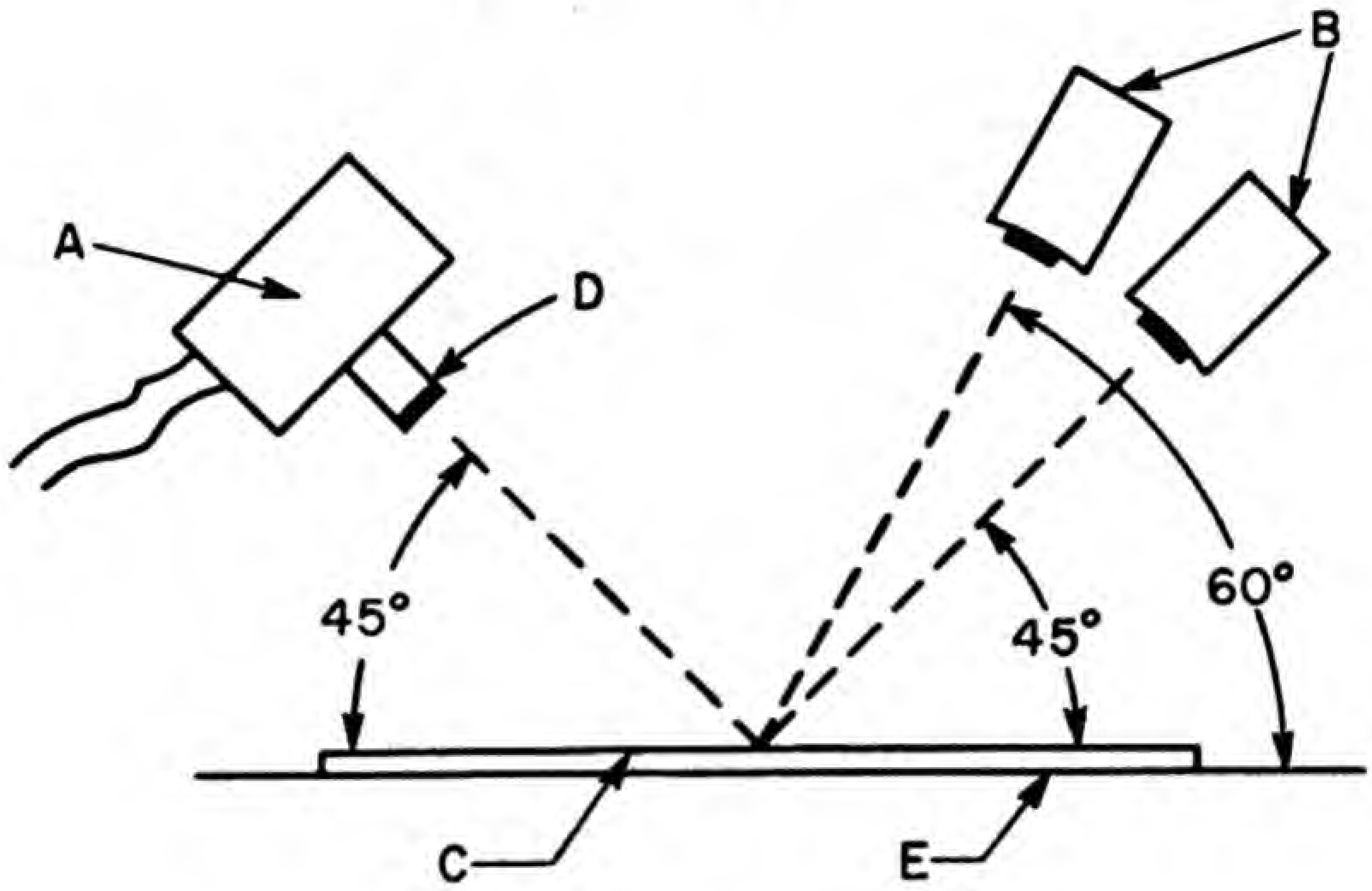

Fig. 2—Glossmeter.

The gloss per cent is determined by means of the following formula:

$$\text{Gloss } \% = \frac{100(I_1 - I_2)}{I_1}$$

where I_1 = exposure meter reading at the specular angle of 45 deg
I_2 = exposure meter reading at the diffused-light angle of 60 deg (15 deg from specular)

The scratch-resistance value I_3 is obtained by dividing the gloss per cent of the abraded surface by the smooth-surface gloss per cent.

2.2 Brush Surface-analyzer Method. A second method used to determine the scratch resistance of the optical material was to scratch the surface by means of falling abrasives, as described in Sec. 2.1, and then to determine the root-mean-square (rms) values of the depth of the scratches by means of a brush surface analyzer or an Abbot profilometer. Since the Project did not have either of these instruments, the scratched samples were taken to the Acme Industrial Co., where a brush instrument was available.

In the brush surface analyzer, a diamond point with a 500-μin. (0.000500 in.) radius is drawn over the test surface. Its up-and-down motion relative to a pair of rounded skids that also slide over the sur-

face is amplified electrically and indicated on a meter. The meter of the brush instrument gives the rms average of the scratch depths in the surface. For most surfaces the rms value is not significantly different from an ordinary arithmetical average. The characteristics of the instrument are such that waviness (waves greater than 0.040 in. in wavelength) is not recorded.

Table 2 — Hardness Readings of Brush Surface Analyzer on Plastics

Run	Material tested	Scratch depth (rms), μin. Crosswise movement of diamond	Scratch depth (rms), μin. Up-and-down movement of diamond	Average rms, μin.	Reciprocal of rms	Hardness*
2	SRL	0.5–0.6	0.4–0.5	0.5		
9	SRL	0.7	0.6	0.65		
				0.57 (av.)	1.76	100
6	Glass	1.2	2.1	1.65		
10	Glass	7.5?	1.0	1.00		
				1.33 (av.)	0.75	42.6
1	SMM	2.8	2	2.4		
4	SMM	2.3	2	2.15		
				2.27 (av.)	0.44	25.0
7	HC201	3.0	3.0	3		
8	HC201	4.0	3.8	3.9		
				3.45 (av.)	0.29	16.5
3	CHM, convex	3.8	3.5	3.65		
				3.65 (av.)	0.27	15.5
5	Styrene, convex	4.3	4.3	4.3		
				4.3 (av.)	0.23	13.0

* Based on depth of scratches with the reciprocal of SRL as 100 per cent.

With the brush surface analyzer the depth of the surface scratches is recorded by the instrument on a moving paper tape so graduated as to greatly magnify the up-and-down motions of the tracer point so that a readable curve is obtained. Values proportional to the scratch resistance of the materials are obtained by determining the reciprocals of the rms values of the various surfaces. In the tests reported here these values were placed on a percentage basis, giving a value of 100 per cent to the SRL. The data on this method appear in Table 2.

2.3 Shore Scleroscope Method. A third method was one previously used with a great deal of success by the writer in measuring hardnesses of surfaces of materials, the surfaces of which had been acted on chemically by active solutions. This method consisted in meas-

uring the depth of penetration of the diamond ball or plunger of a Shore scleroscope, penetration being produced by repeated bounces on a given spot of the surface whose hardness is being measured. The Project does not have a Shore scleroscope, but Northwestern University made one available to Project workers.

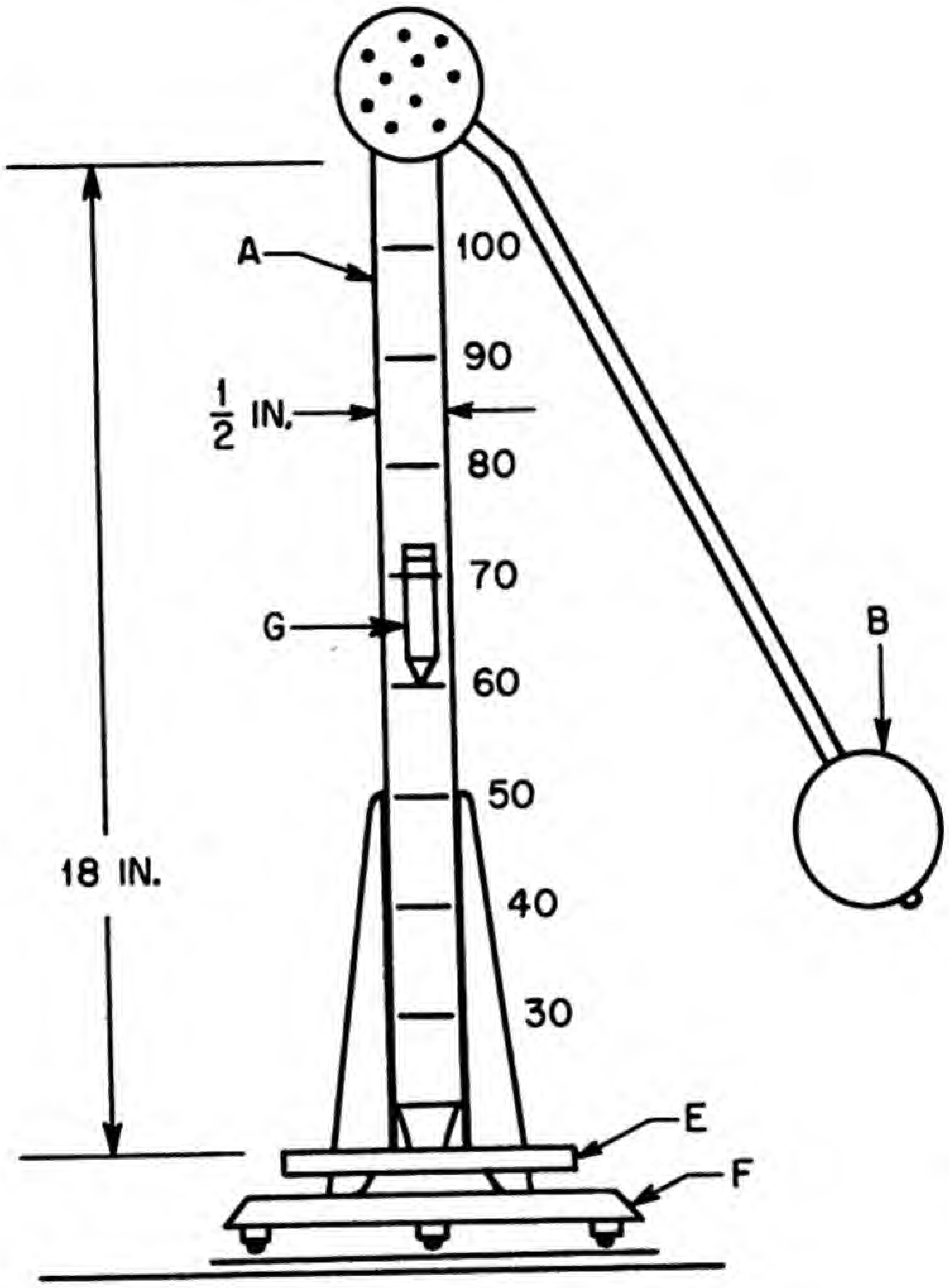

Fig. 3—Scleroscope.

The scleroscope (see Fig. 3) consists of a glass tube about 18 in. long with an internal diameter of about ½ in. A plunger G travels up and down in this tube. There is a tapered diamond embedded in the lower end of this plunger. By pressing on the bulb B, a vacuum is formed in B, and G is drawn to the top of the tube. By pressing bulb B again, the plunger G is released and it falls the length of tube A onto specimen E, held on the base of the machine F. After hitting the specimen, the plunger rebounds and the height of the rebound is read on a scale. This value represents the hardness of the specimen being tested. In this work the height to which the plunger rebounded was not used. Instead, the plunger was dropped 30 times on a given spot;

the specimen was removed; and by the aid of a high-powered microscope the diameter of perforation of the plunger on the surface was measured. The reciprocals of these values are proportional to the scratch resistance of the materials being tested. These values were next placed on a percentage basis, giving a value of 100 per cent to SRL. For the results of this method see Tables 3 and 4.

Table 3—Shore Scleroscope Readings on Plastics

Run	Spot	Plastic	Diameter of penetration: 25× B and L microscope, divisions	Diameter of penetration: 100× No. 1019 microscope, divisions	Diameter of penetration: 100× No. 1019 microscope, mm	Penetration reciprocal, mm	Hardness*
1	1	SRL	½	1½	0.249	4.0	100
2	2	CHM	¼	2	0.333	3.0	75
1	1	HC201	1	3	0.500	2.0	50
2	2	SMM	1½	5	0.830	1.2	30
1	1	PS†	3	8½	1.411	0.71	18

*Based on reciprocal reading of SRL as 100 per cent.
†0.4 in. thick.

Table 4—Shore Scleroscope Readings on Polystyrene: Reduction in Rebound on Successive Bounces, Run 1, Spot 1

Bounce	Scleroscope reading	Bounce	Scleroscope reading	Bounce	Scleroscope reading
1	75	11	70	21	58
2	81	12	30	22	55
3	60	13	65	23	53
4	75	14	62	24	50
5	76	15	60	25	52
6	73	16	55	26	56
7	75	17	53	27	57
8	70	18	62	28	40
9	72	19	58	29	52
10	72	20	62	30	50

3. CONCLUSIONS

As indicated in Table 5, SRL was found to be the most scratch resistant by all three methods. However, the mar-resistance and brush-analyzer results, indicating SRL to be superior to glass, may be misleading because the falling abrasive may shatter the glass or cause

fissures to form owing to the brittleness and lack of toughness of the glass. Perhaps a more satisfactory comparison of glass and plastics could be made by moving a sample strip, which supports a given mass, over a piece of very fine silicon carbide abrasive paper at a constant rate.

Table 5—Summary of Hardness Determinations by Four Methods

Material tested	Mar resistance (Table 1), %	Brush analyzer (Table 2), %	Shore scleroscope (Table 3), %	Rockwell
SRL	88	100	100	
Glass	50	42.6		
SMM	25.9	25.0	30	M-70
HC201	19.7	16.5	50	.
CHM		15.5	75	
Styrene	16.2	13.0	18	M-87 to M-90

By all three test methods, SMM is harder or more scratch resistant than styrene.

It is recommended that SRL be subjected to radiation-energy tests at the Clinton pile to determine if it can withstand this energy for longer periods than glass before turning dark. If it is superior to glass, it should be considered for use as lenses or windows in new optical equipment.

Paper 5.1

LIGHT TRANSMISSION THROUGH A WATER-FILLED TUBE*

By George S. Monk and H. W. Ibser

ABSTRACT

It has been observed that "blacking-out" of the light transmitted through water- and slug-filled tubes occurs subsequent to stopping the flow of water. Some definite association of temperature gradient and blacking-out appear to be established by the experiments reported here.

An extremely interesting phenomenon, first observed by Moon and his group, may be characterized as "fading." Although a light beam passed down a pile tube as well in running water as in air, it was extinguished after the water flow was shut off. In order that pressure be maintained, a valve was closed at the exit end of the tube to shut off the water flow. As the valve, which operated slowly, was closed, there was no noticeable effect until the instant when the valve gate finally closed. Then a series of appearances occurred which are sketched in Figs. 1, 2, and 3. Complete obscuration occurs in about 5 sec. Each of the figures represents the same segment of the annulus. The concentric lines in the annulus represent diffraction which is always present.

The most obvious characteristic of the fading was the beginning of an irregular outline of shadow at the outer periphery of the annulus. A much smaller and somewhat delayed outline of shadow began on the inner periphery adjacent to the slugs. The shadow finally grew until it closed the entire annulus and no light was seen. After several

*This paper is based on Reports CP-2298, Oct. 28, 1944; MUC-GSM-160, Oct. 31, 1944; and MUC-GSM-170, Dec. 4, 1944.

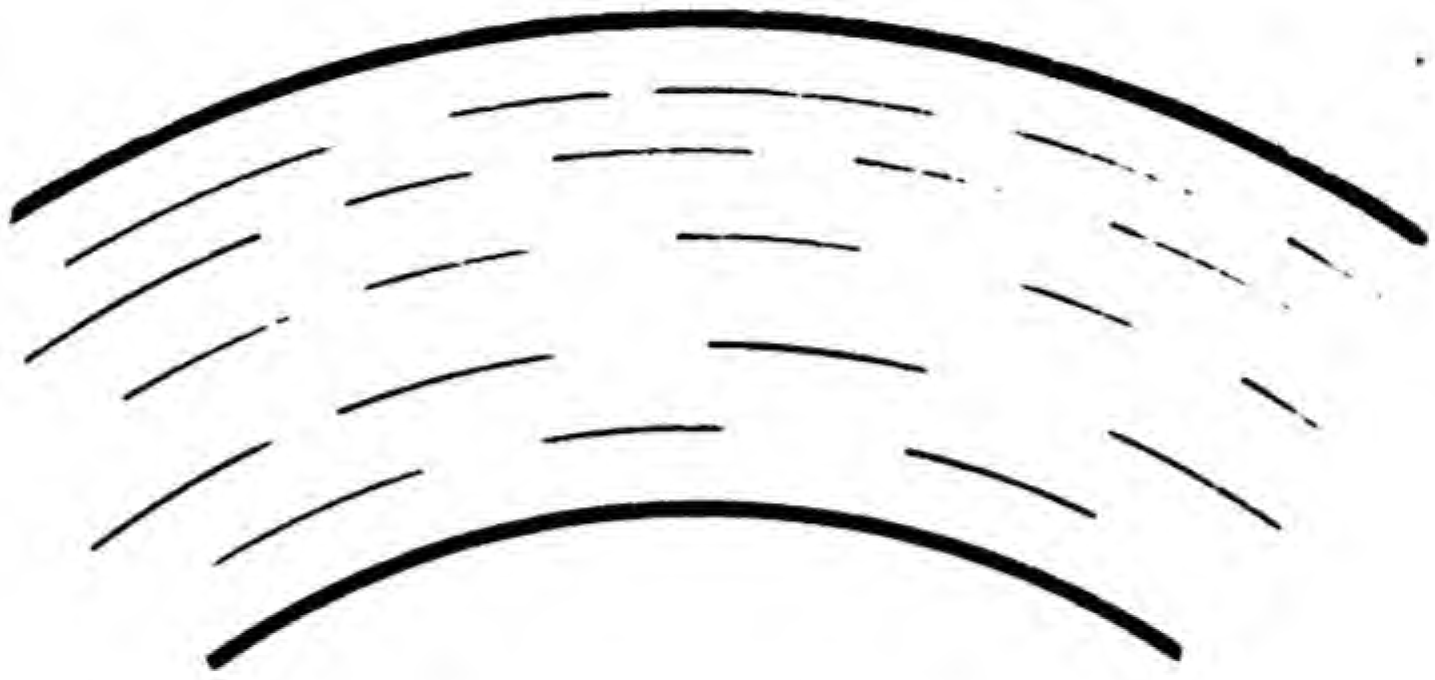

Fig. 1—Light transmitted through the annulus with water running.

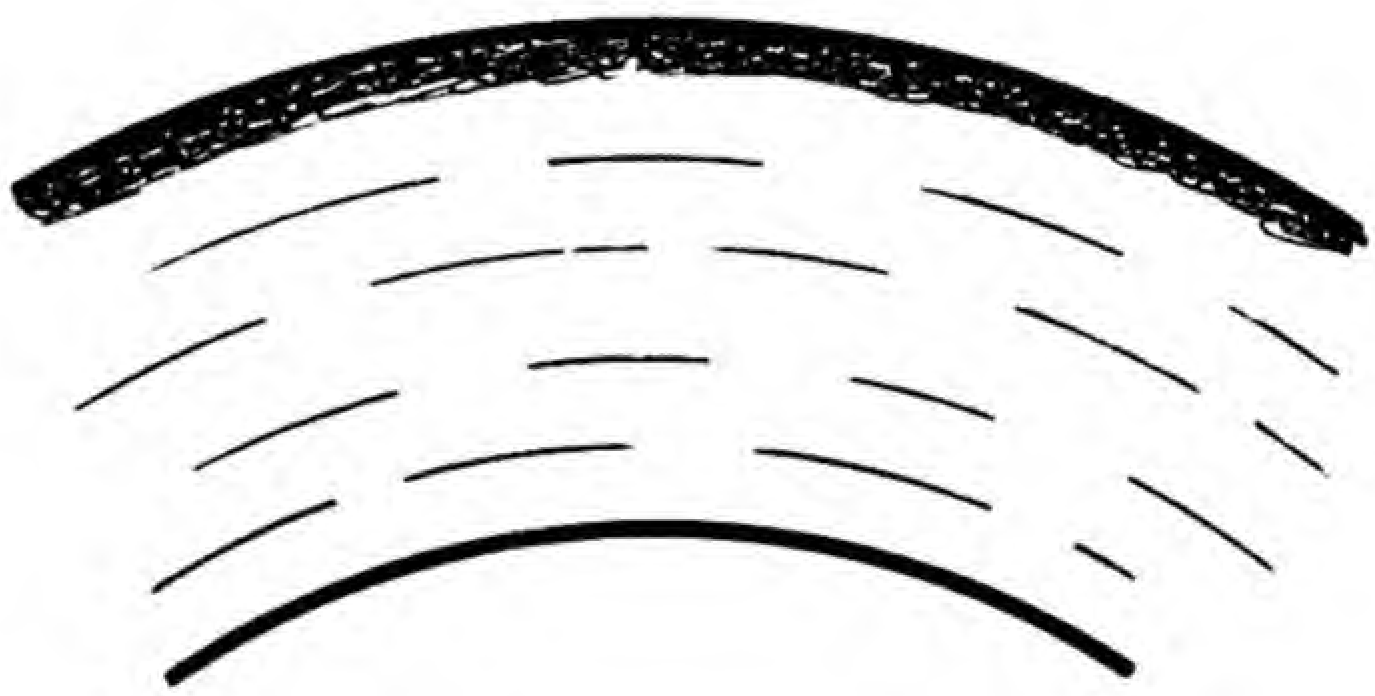

Fig. 2—Blacking-out starting at the outside edge of the annulus at the instant water stops flowing.

Fig. 3—Continued blacking-out 2 to 3 sec after water stops flowing.

hours the light began to come through the still water in the tube once more.

Several hypotheses have been proposed to explain the observed phenomena, and it was felt that some experiments should be performed to determine what factors might control the passage of light through a pile tube. To this end, a 20-ft length of pile tubing was provided with end caps through which light could be passed along the tube while water was forced through it. Continuous aluminum pipe of suitable diameter was used to simulate slugs. The assembly was supported at six points along its length by wood supports (2 by 4 in.) which held it about 10 in. above a long stone bench. McCorkle estimated 20 psi as the pressure of the (tap) water supply used. Distilled water at the low pressure of about 5 psi was also used, being forced out of a 5-gal jar by compressed air. (The total capacity of the tube system was about 2 gal.) Temperature gradients were established by regulation of the temperature of the water before introduction into the tube and by using gas flames to heat the tube exteriorly. A 150-watt reflector flood lamp was used as a light source.

It was found impossible to pass light through the tube while tap water was flowing through it, almost certainly because this water was far from clean. After standing in the tube for some time, however, the water became transparent to the extent that a narrow but fairly bright line of light could be seen surrounding the inner tube except at the bottom (between the ribs) and a small interval at the top. The lower and upper obscurations were probably caused by sediment and bubbles, respectively. The possibility of temperature affecting the temporary opacity of the water can be discounted because the light could not be transmitted, even when the temperature of the water was adjusted to that of the room, unless several hours was allowed for settling. Quite apparently, the tap water supply was not suitable for study.

The first trials with distilled water were uneventful. At room temperature, of course, it was transparent. When cooled to about 45°F and passed through the tube with the ambient air temperature 25°F higher, it seemed to transmit the light even better and to be quite independent of any temperature gradient whether flowing or standing still. Perhaps this was because the air was less effective for conducting heat to the tube than was the graphite surrounding Moon's pipe.

The peripheral incidence and radial progression of the fading of the light in Moon's tube might be expected when the increase in opacity of the water was general and homogeneous. To simulate such conditions, the floodlight was slowly dimmed with a Variac. As the

source became dimmer, the light reaching the eye seemed to come (largely by reflection from the tube walls) from farther and farther down the tube, which made the circle of light seem to become progressively thinner and smaller. However, it is unlikely that this would account for the results described by Monk.

At Monk's suggestion, an attempt was made to produce a thermal gradient by means of gas flames, and the light was extinguished in about 20 sec. Subsequently, it was found possible to change the light pattern very noticeably by applying one's hand to the tube filled with water at room temperature, the change consisting of a localized increase in brightness near the periphery of the water annulus under the point of contact. The light could also be bent by applying ice to the tube. The gas-flame heating did not produce a change in the tube temperature easily detectable to the hand, nor did the application of the hand; the ice cooled it quite perceptibly.

On the strength of these experiments it seems quite safe to predict that any method of slug examination dependent on the transmission of light through a tube in an operating water-cooled pile would be extremely unreliable because of thermal effects. More closely controlled experiments will be necessary for a more precise explanation of the trouble.

Paper 5.2

REPORT ON SMOKE TESTER*

By W. G. Bouricius

1. INTRODUCTION

The Optics Section was requested to design and construct a smoke tester to determine the size of smoke particles approximately ¼ μ in diameter and with specific gravity of 1 or 2. This paper is a summary of the work done by K. F. Whitcomb up to Mar. 10, 1944, and of the concluding work done by the writer.

2. SUMMARY AND DESCRIPTION OF INSTRUMENT

With particles in the ¼-μ range it is necessary to have some magnification, and a small ocular-model micrometer at once suggested itself. By preliminary calculations it was determined that a 40× magnification would enlarge the particle sufficiently so that it would be observable. A 40× ocular micrometer was obtained with a field of view of 0.12 cm on the stage; each small division represented 0.004 cm. With this micrometer it was theoretically possible to observe a 10-min fall of particles of specific gravity 1 and a 3-min fall with particles of specific gravity 3.5.

The stage was a hollow chamber in a block of copper. Copper was used to equalize quickly the temperature in all parts of the chamber and thus to avoid one cause of convection currents. To avoid outside air currents through the chamber, windows were attached. A small pen light was used to illuminate the stage from an angle such that no direct light entered the optical system. The particles were observed by reflection and refraction of light.

*This paper is based on Report CP-3022, June 1, 1945.

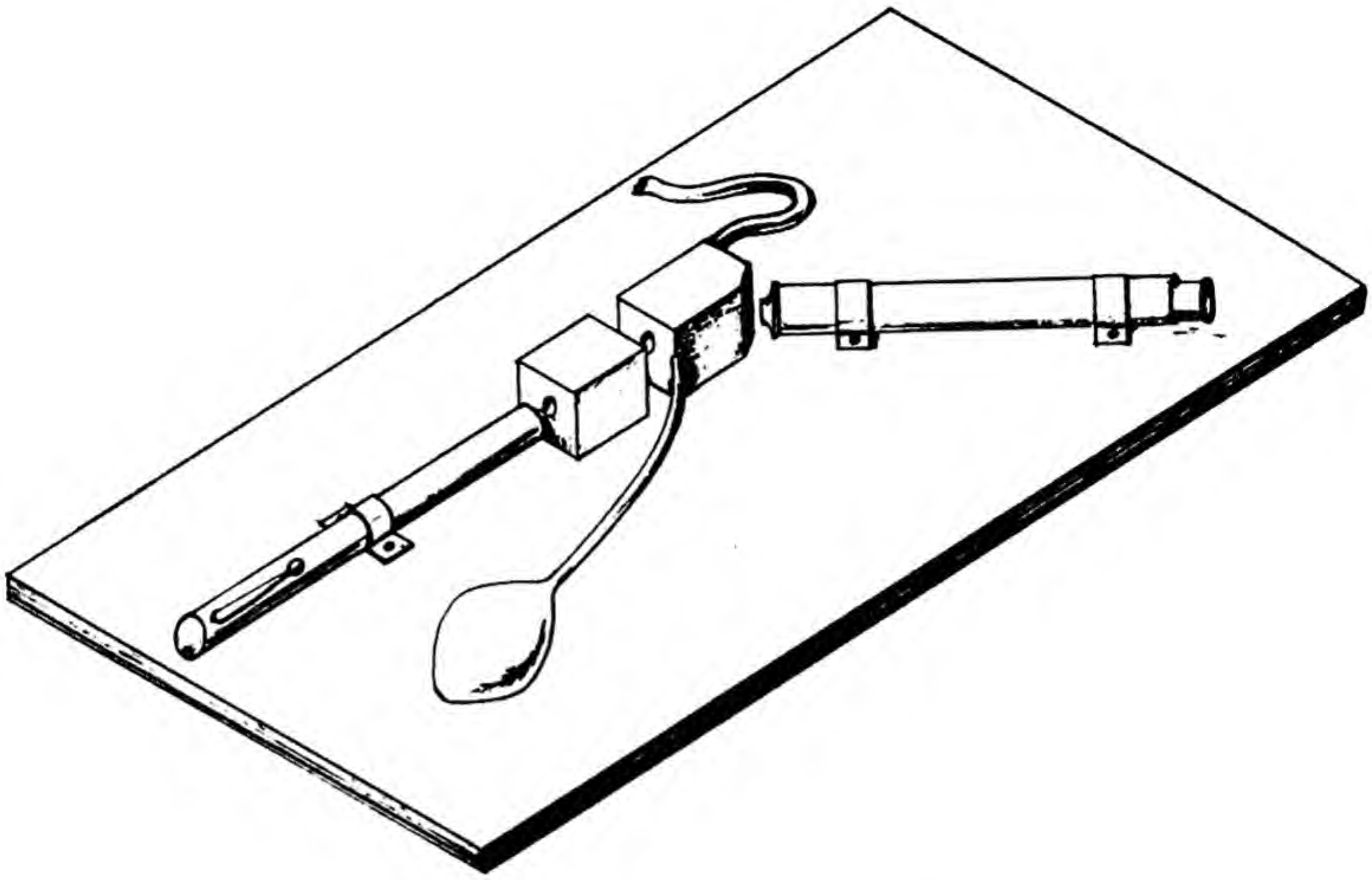

Fig. 1—Early smoke tester.

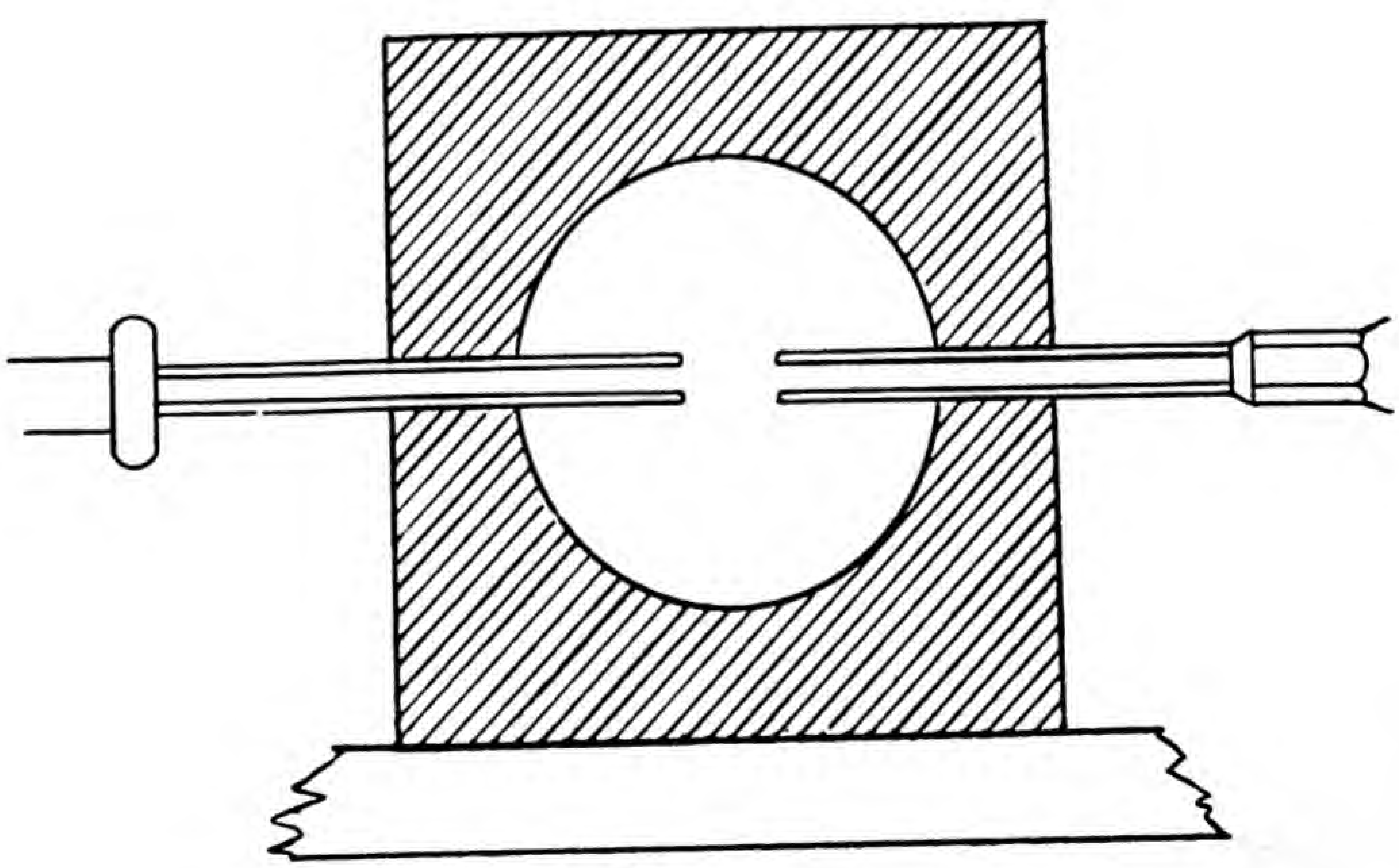

Fig. 2—Final smoke-tester chamber design.

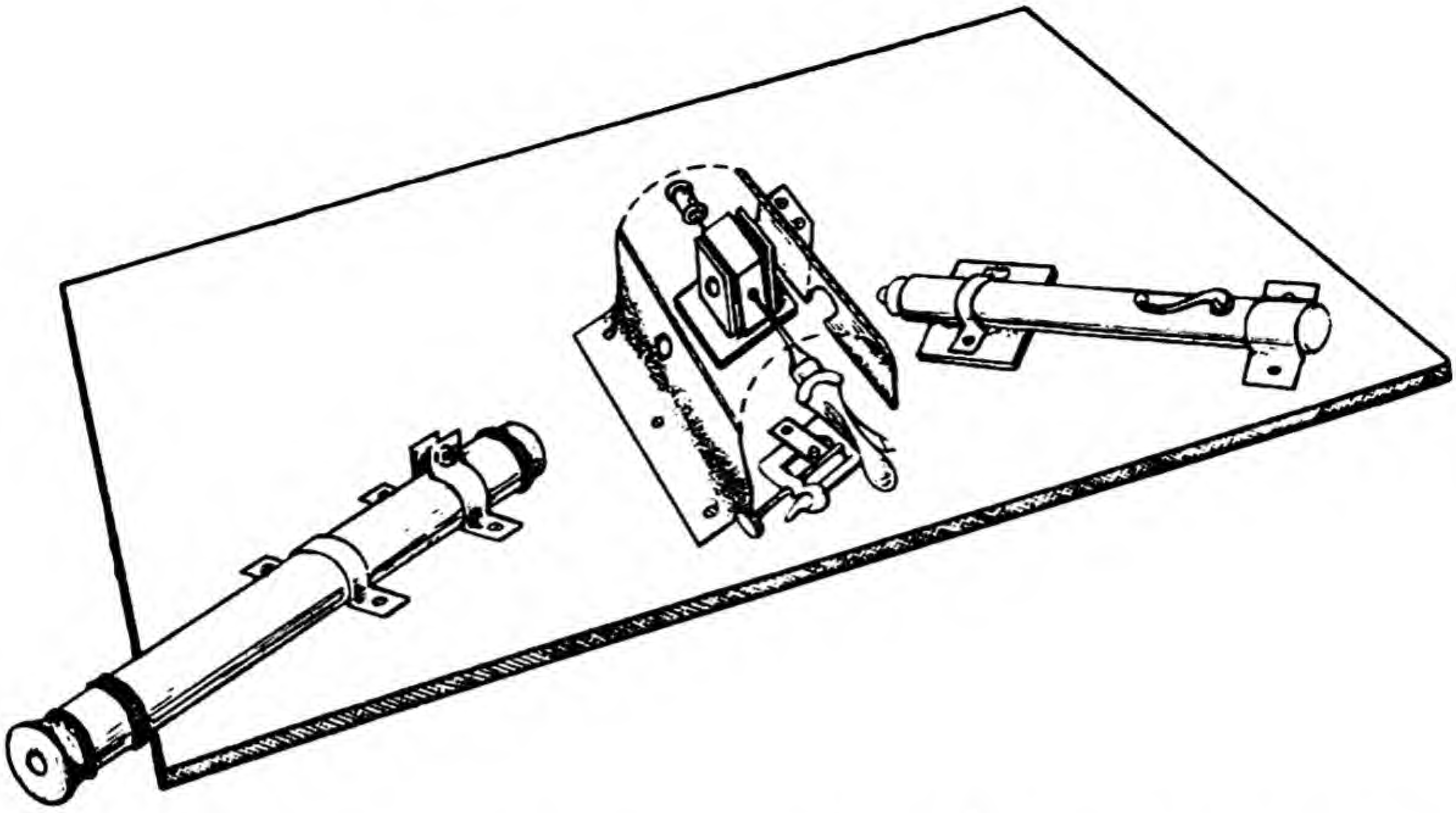

Fig. 3—Final smoke-tester arrangement with a hood over the vital parts.

The particles were introduced into the chamber by sucking smoke into a syringe bulb and then blowing it into the chamber through a rubber tube. A band of smoke was desired that would be steady and without convection currents. Whitcomb attempted this by putting a clamp on the bulb and by having a chamber shaped as in Fig. 1. This model was field tested and returned for further improvements.

Various other arrangements were tried, e.g., brass nozzles, glass nozzles, glass tubes with holes in bottom, ledges, etc. Each had one or more faults such as swirling smoke due to lack of streamlining, convection currents, no band of smoke, too rapid flow of smoke, unsteady atmosphere, lack of control of inlet and outlet of the smoke, dust on windows, or insufficient illumination.

The final design, which was the only successful model, was as shown in Fig. 2. Two small hypodermic needles were thrust through the holes, and the ends of these needles were polished in a lathe. The windows and the needles were attached with celluloid cement. The chamber was necessarily wide (3/8 in. minimum) so that dust on the windows would not interfere with observation of the particles. (The depth of focus of the microscope is rather large.)

A smaller smoke chamber, the bulb from an "eye-dropper" pipet, was attached to one needle. A pinch clamp on it sufficed to suck in air and any particles in the air. A trial run in a cigar-smoke-filled room convinced the operators that the limit of precision using this method had been reached. Figure 3 shows the final arrangement with a hood over the vital parts.

Paper 5.3

BORESCOPE CAMERAS*

By R. L. Williams and W. H. McCorkle

ABSTRACT

Acceptable photographic records have been obtained with a 35-mm camera designed and constructed for use with borescopes. Descriptions are given of this 35-mm camera and of a 16-mm camera designed to incorporate the features most desired in a camera for borescope and related uses.

1. INTRODUCTION

The desirability of having photographic records of objects which must be examined through a borescope or other borescope-type instruments led to this study and the design and development of the cameras described.

2. INITIAL EXPERIMENTS

Test exposures were made using a 3¼- by 4¼-in. camera (Fig. 1), with only a 4-ft standard borescope section coupled to the borescope crossarm and a small 3-cp light in the borescope head. A minimum exposure of 15 sec was required to yield even a very thin negative on Agfa Superpan Press film. As additional sections of tubing were added, the exposure time increased, until, with 40 ft of tubing coupled to the borescope, an exposure of 15 min was required to produce a usable negative. At this full extension, it was impossible visually to focus the image formed by the borescope lenses on the ground-glass screen.

* This paper is based on Report CP-3128, Aug. 15, 1945.

The 3¼- by 4¼-in. camera was discarded as unsatisfactory for the following reasons: the visually focused image did not fall in the film plane; there was insufficient light for focusing the image on the camera ground glass; the 1¼- by 2-in. filmed image represents un-

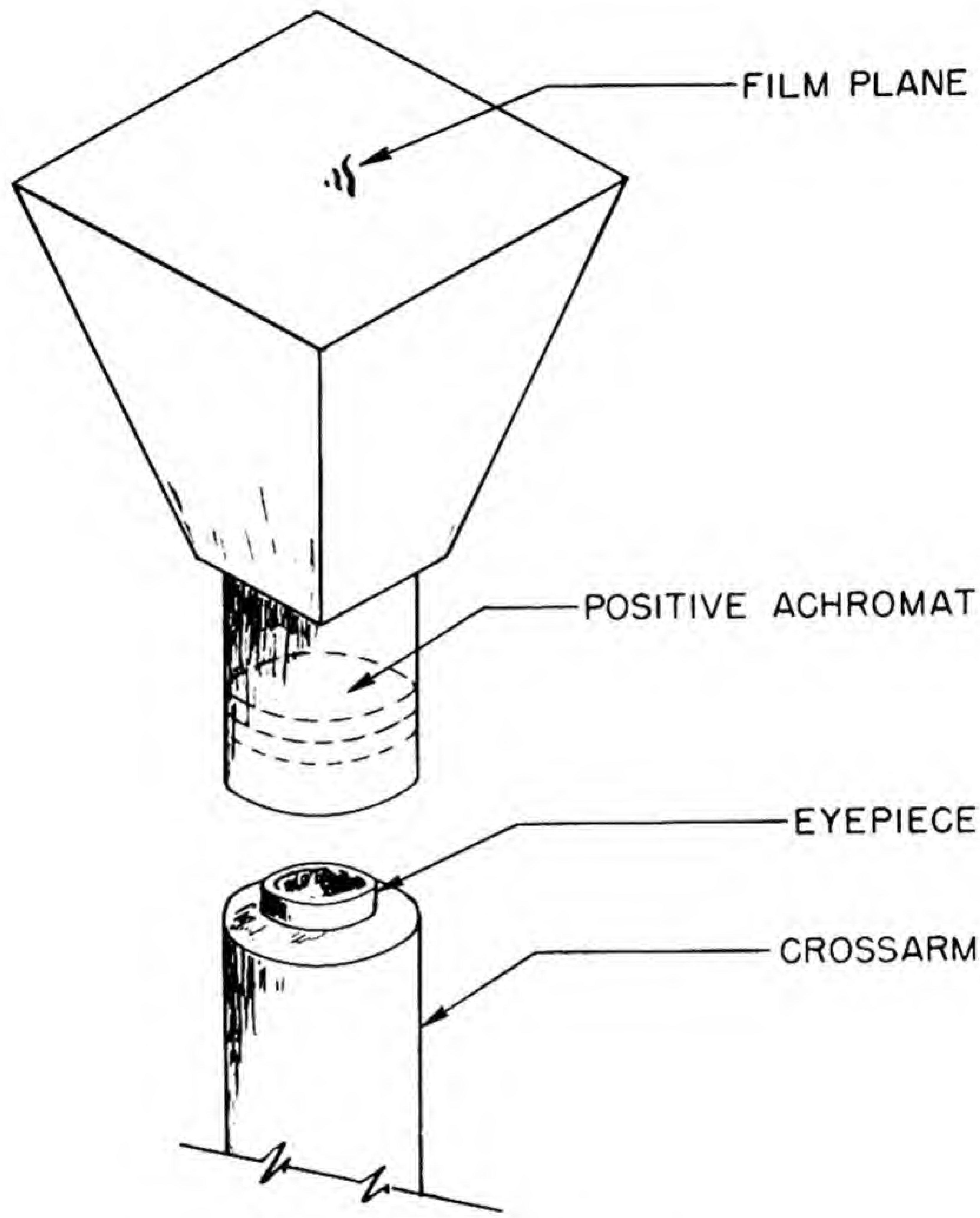

Fig. 1—Camera purchased for use with a borescope.

necessary magnification; excessively long exposures were required; and the achromat supplied with the camera was not a photographic lens. The achromat did not give a good image even when stopped down by the pupil of the eyepiece.

Exposures that were made on 35-mm film utilizing the camera lens and the borescope eyepiece were too long also. Readable films were obtained with 4-sec exposure even with 40 ft of tubing connected to the borescope and with exposures that were made using only the camera box and the objective-lens system of the borescope.

This improvement was due to the increase in the intensity of the light activating the film because of the reduced image size and the elimination of the eyepiece- and camera-lens systems as light-absorbing and light-reflecting surfaces. Still further shortening of the exposure time can be expected with the change from a 3- to a 21-cp lamp in the borescope head.

3. A SATISFACTORY 35-MM CAMERA

A new camera unit, shown in Fig. 2, was designed around the body of the Perfex 55 camera. This camera was chosen because it has a

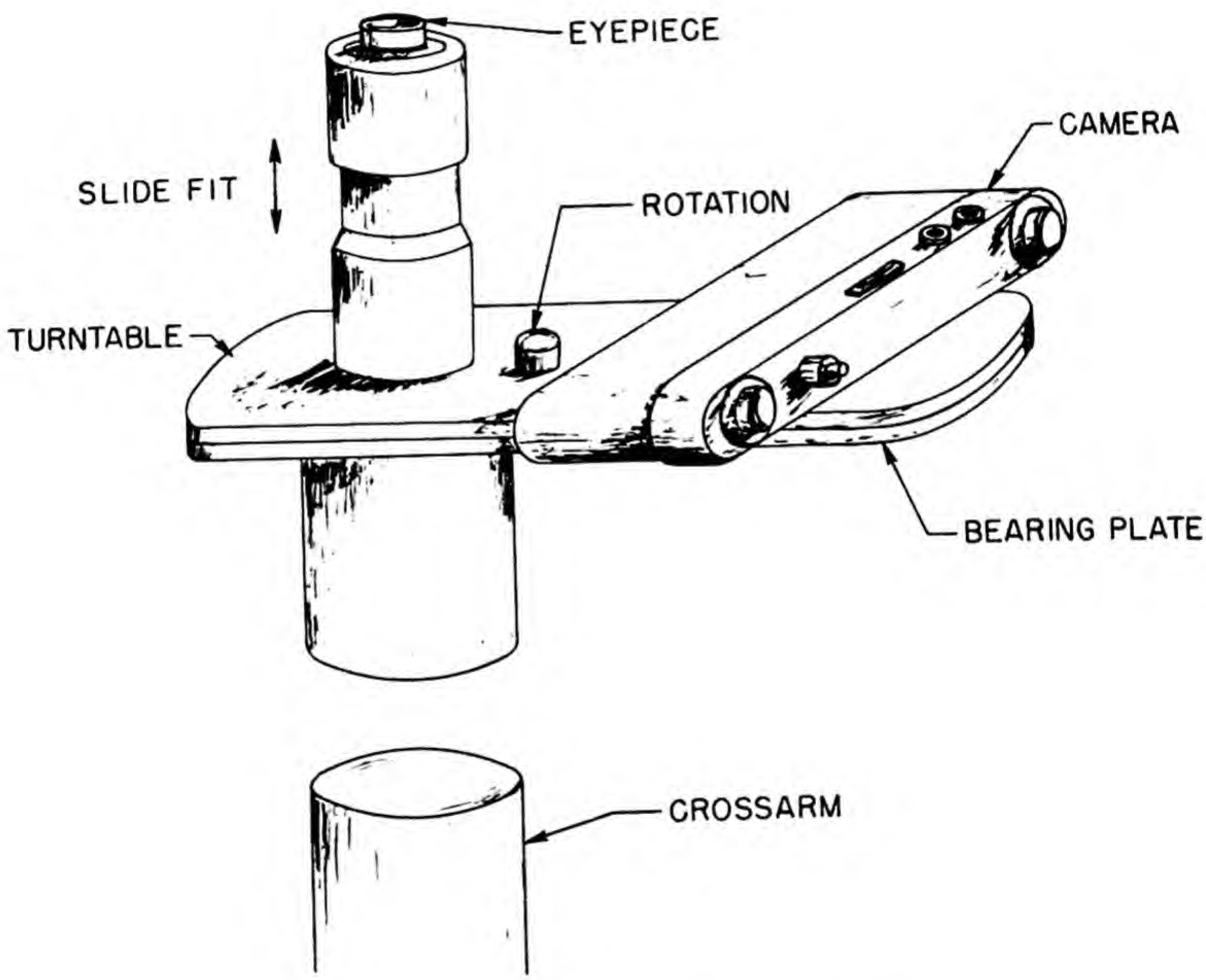

Fig. 2—A satisfactory 35-mm camera.

focal-plane shutter which prevents the film from being exposed when the turntable is rotated; also, it is possible to remove the entire camera unit from the borescope without danger of exposing the film; and the necessity of interposing a shutter system within the borescope arm is eliminated. To facilitate the change from visual observation to photography, the equipment was designed to mount both the camera and the borescope eyepiece on a brass turntable. A second

plate, made of aluminum, was used as the bearing surface for the rotary brass plate. The aluminum plate was threaded to an aluminum tube which slipped over the outside of the borescope arm and which mounted the entire unit to the borescope. To focus the borescope image in the film plane, a glass reticle was inserted in the eyepiece tube with the cross lines in the same relative plane as the film. The eyepiece was made adjustable with a slide fit in order that parallax methods of focusing could be used. Tests showed that with this method no difference of focal adjustment smaller than 0.08 in. could be made. Since the focusing lens has a focal length of 22 in. and an aperture of 1.2 in., the largest circle of confusion introduced with careful focusing is about 0.005 in. This is expected to be better than the definition afforded photographically.

In the construction of other similar attachments, it would seem advisable to use a brass bearing surface as the lower table and to mount a complete aluminum disk as the table for the camera and eyepiece. This disk would have to be of the smallest possible diameter to permit access to the camera shutter mechanism. With this change it would also be possible to change the locking method of the turntable from the present taper pin to a ball-bearing notch method. The lower brass bearing surface would not be a complete disk, and consequently the total weight would not be appreciably increased.

This type of camera unit can be attached to the underwater periscope, the blind-bore borescope, and other instruments of this type. In addition, permanent records can be kept of the images formed by various lens setups used in laboratory design work. In photographs taken with the blind-bore head, utilizing a deep-field objective, the usable depth of field is only somewhat greater than 1 in. By visual observation, considerably greater depth of field is obtainable with this objective because of the ability of the eye to accommodate over a larger image distance than it is possible to do photographically. However, greater depth of field could be obtained photographically by increasing the intensity of the light source and introducing an adjustable diaphragm.

4. DESIGN OF A 16-MM CAMERA

In the interest of achieving faster exposures, further experiments were conducted using 16-mm film. This reduction from the 35-mm size shortened the exposure by a factor of 4. A lens 5 in. in focal length, forming an image 9.5 mm in diameter, had to be added to the lens system of the crossarm to reduce the image size for this small film. One departure made from standard 16-mm practice was the change in frame size from 8 by 9.5 mm to a square 9.5-mm frame in

order to include the entire field of view. To utilize this speed increase, a new camera had to be considered. The requirements for a unit of this type are single-frame exposure, variable shutter speeds from 1/100 sec through time exposure, film spools of the roll-film type, built-in film-cutting knife to cut off any number of exposures

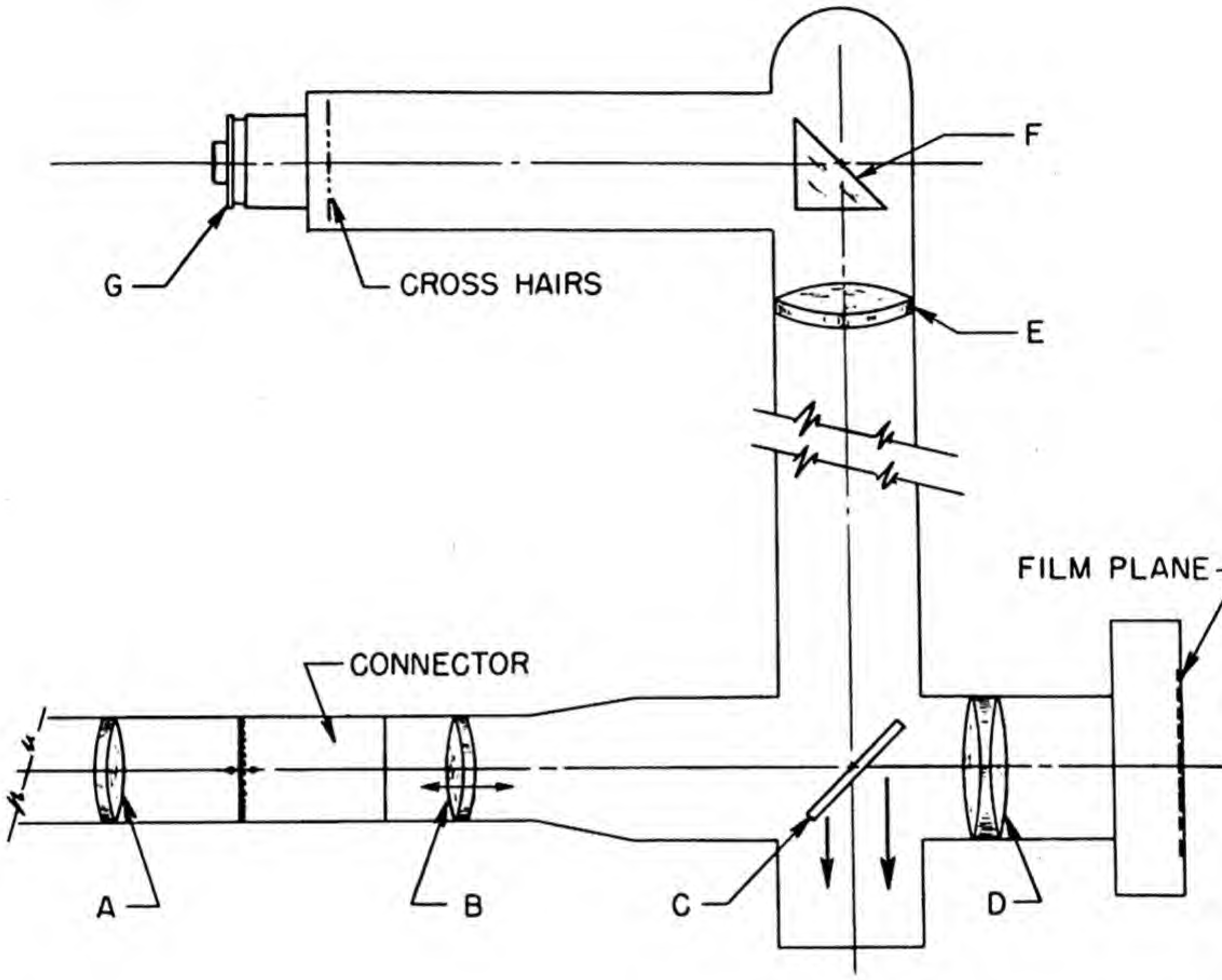

Fig. 3 — Proposed arrangement of the 16-mm camera on a borescope cross-arm.

before completion of the full roll, and compactness and small weight. The only commercial 16-mm cameras available were motion-picture cameras; these cameras had no variable shutter speed; they were either too large or too heavy; they were in units containing a single-frame mechanism; and they used magazine loads instead of roll film. Because no suitable commercial cameras were available, a 16-mm still camera was designed to fill the needs.

Before a final decision on camera design could be reached, it was necessary to investigate the different methods and positions for mounting a smaller-type unit. The design shown in Fig. 3 would establish coordinated focus between the eyepiece and the camera by

making lens B movable. The parallel rays produced by this lens are focused either by the camera lens D when mirror C is withdrawn or by the crossarm lens system E,F,G when the mirror is in the

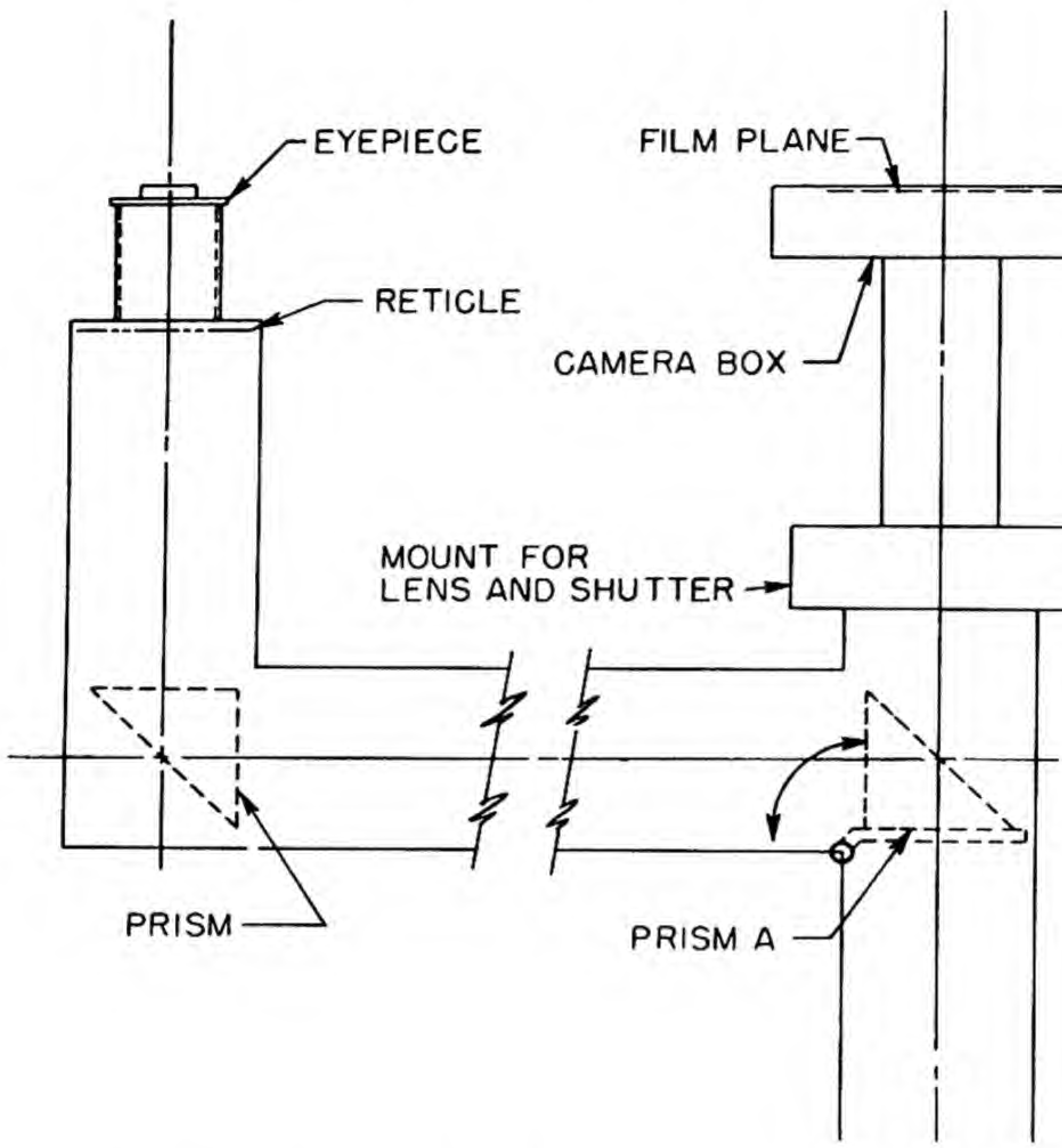

Fig. 4—Alternate arrangement for attaching the 16-mm camera to a borescope crossarm.

indicated position. Cross hairs ahead of the eyepiece G, registered with the film plane behind the camera lens, and a sliding fit for adjusting the eyepiece for individual variations of the human eye would assure perfect focus by parallax methods. A mounting of this type overcomes the disadvantage of extra added weight to the crossarm; it was rejected, however, because it places the camera in direct line with the radiation from the tube, thereby subjecting the film to radiation and possibly endangering the operator as he adjusts the camera mechanism. The smaller film size, coupled with a well-designed lightweight camera, makes it possible to mount the camera safely on the crossarm as shown in Fig. 4. Prism A is pivoted and can be

removed from the light beam when photographs are taken. The offset for the eyepiece accounts for most of the additional weight in this design, but it is still within a safe weight limit. Variations of shutter speed are secured by rotating the indexed ring on top of the shutter-lens unit. Focusing is again done by parallax methods, utilizing the glass reticle in the eyepiece arm. The reticle is precision adjusted, and neither it nor the camera unit can be removed from the arm without throwing the entire unit out of adjustment. Figure 5, taken from the working drawings, shows sectional views of the camera box. As designed, this camera fulfills the following seven conditions: single-frame exposure (9.5 by 9.5 mm), daylight loading stock and take-up spools, lock mechanism to prevent double exposures, self-cocking shutter with speeds from $1/100$ sec through time exposure and bulb, maximum of 200 exposures per camera loading, automatic exposure counter, and film-cutting knife to permit removal and development of any number of exposed frames.

The exposed films made with this camera can be utilized in two different ways at the discretion of the operators. If the final result is to be prints, the procedure followed is straight development of the exposed film with prints of the desired size made by enlargement. However, if the operators wish to view the image by projection, reversal development will yield positive transparencies suitable for projection. If the projection method is considered more satisfactory, the writers would advise that the original film be developed to a negative only and positive transparencies on film be made from the master negative, thereby eliminating any danger of scratching or otherwise damaging the master negative through repeated handling. The positives can be printed on 16-mm film by contact, or they may be enlarged to 35-mm film. In choosing one of these two methods it is important to bear in mind that a properly exposed negative will record a brightness scale of 160 to 1, whereas the print that is made from this negative will record a reflection-brightness scale of only about 40 to 1. However, if a good transparency is made from the negative, almost the entire 160-to-1 scale can be retained, especially if the transparency is viewed by transmitted light, as in projecting on the reverse side of a translucent screen, rather than viewing it by reflected light, as in projecting on the front surface of a reflecting screen.

Inaccuracies may result from fatigue of the observer's eyes when examining the entire length of the inside of a pile tube. This could be eliminated by installing a completely automatic 16-mm still camera functioning as a modified motion-picture camera. For this work it would be necessary to modify the design of the present borescope gear

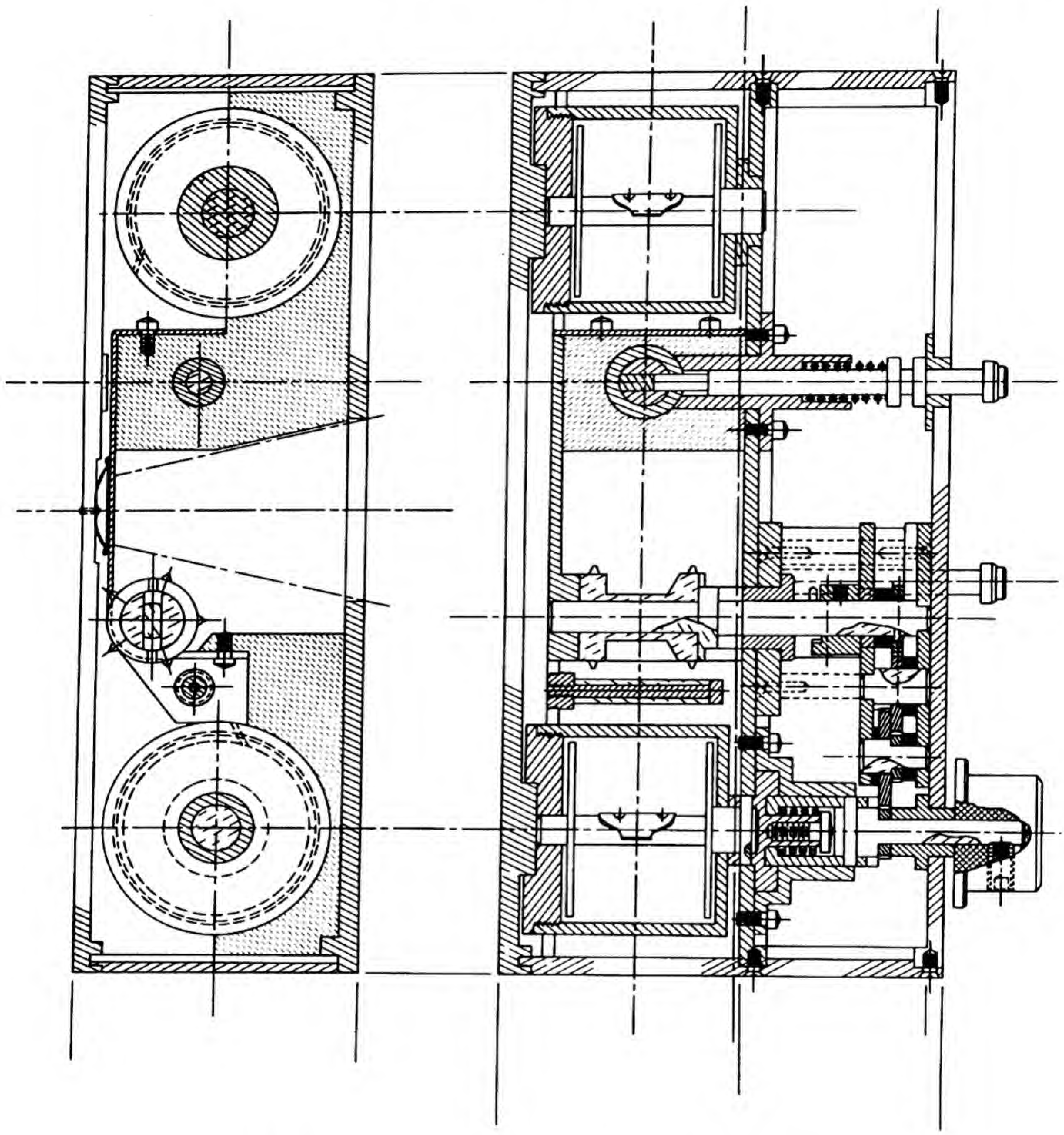

Fig. 5—Sectional views of the camera box.

box from continuous motion to an interrupted advance of the borescope. The camera would be synchronized to make an exposure during the pause in the borescope's motion. The only manual operation then involved would be coupling new sections of tubing to the borescope. This type of camera merits serious consideration because of the time saving, the minimizing of the factor of human error, and the fact that a permanent record of the inside of the entire tube is obtained.

Paper 6.1

WATER-FILLED WIDE-ANGLE VIEWERS*

By George S. Monk

1. INTRODUCTION

The use of a wide-angle viewer for observing the inside of an irradiated space was developed by the Optics Section in 1943. Its development grew out of six months of study of numerous devices for viewing such spaces. It was finally decided that systems for this purpose could appropriately be classified under two heads: (1) periscopic systems containing lenses for placing an image of the eye inside the enclosure and (2) over-all viewers of the type discussed here.

2. GENERAL CONSIDERATIONS AND CONSTRUCTION OF VIEWERS

The simplest approach to the problem of viewers was set up. This involved the use of a plastic window of suitable dimensions placed at the end of a tank of plain water or water containing radiation-absorbing salts. This combination forms a thick negative lens. The operator, looking through a plain surface at the other end of the tank, could see everything in a room over an angle of view which depended on the following factors:

1. The diameter of the plastic window and its radius of curvature
2. The length of the tank
3. The index of refraction of the liquid (the higher the index, the larger the angle of view)
4. The possible addition of other negative lens elements in front of the plastic window
5. The distance of the observer from the rear window of the tank

*This paper is based on Report MUC-GSM-126, July 6, 1944.

It was also proposed to use an auxiliary telescope of the erecting type to get a magnified image of any detail which was to be scrutinized more closely.

The disadvantages of the viewer, which cannot take the place of a periscope, may be elaborated as follows:

1. The liquid may need frequent changing.
2. If salts are used, they may be colored by radiation.
3. If salts are used, they may attack the container.
4. A negative lens has bad distortion. To compensate for this, a distortionless lens has been theoretically developed, but the speed required in servicing Project sites bars its use at present.
5. No really satisfactory auxiliary telescope has yet been made. Procurement of lenses of sufficient size is the chief difficulty.
6. There is some color aberration, especially at the edges of the field.
7. The large opening required for the viewer, as compared to the small opening required for a periscope, increases hazards to personnel. These hazards are not always present, but when they are they are principally due to the danger that the liquid may run out of the tank.

The advantages of the viewer are:

1. It is possible under extreme circumstances to get an angle of view as large as 150 deg.
2. The observer may simply stand behind the viewer and look over a large area very rapidly. No scanning mechanism is required.

The first approach to construction was to have made plastic disks which, when mounted on the tank, gave a concave surface at the front end. Some time later, a supply of North American Aviation, Inc., airplane lenses was acquired, and these were put on exhibition and approved for general viewing purposes subject to the limitations given above. These lenses were constructed to be mounted in the cockpit of a plane in order that the flier could see the entire sky above him. When so used, the observable view is slightly larger than a hemisphere. When the observer is farther away, the view becomes less and the image becomes smaller. The diminution of image size is a disadvantage when used in viewing tanks. This extreme disadvantage has been partly overcome by putting water against the rear surface of the lens. This results in an increase of image size. It is still true, however, that the North American lens was a device adopted for expediency because they already existed in quantity. It is still more important to keep the length of the tank down and increase its width.

The adoption of this lens also makes the use of a liquid with an index of refraction higher than that of water desirable. Some experiments[1] have been carried out at the Clinton pile to test the efficacy of salt solutions in the presence of radiation, and the results are fairly satisfactory. Although the salts used became slightly yellow, inhibitors of the yellowing could be added. More important, turbidity did not occur. Other tests (see Paper 6.2) have been made by the Chicago Optics Section, and it is found that solutions of sodium nitrate and zinc chloride do not become turbid and do not attack materials commonly used for containers. Figures reported by Way[2] may be interpreted to indicate that, if such salts are used, the tank can be about two-thirds as long. It should be mentioned that the test samples prepared by the Chicago Optics Section have not yet been subjected to radiation, but similar tests elsewhere show that the solutions will be satisfactory.

Persons who have looked through the sample viewers in the laboratories of the Optics Section have found them satisfactory, but in nearly all cases they have looked through viewers which conform to the restrictions mentioned above, in the sense that the viewer was short, of relatively large diameter, and the observer was close to the rear face. Unfortunately, however, viewers have been adopted for certain sites and made so long that the limitations stated above were exceeded, or they have been placed in such a position that the observer was many feet away. The Optics Section does not endorse such usage.

This type of viewer has recently been adopted for observing the rear face of a pile. The Optics Section feels that this instrument exceeds some of the limitations mentioned above and would like to have a thorough review of the possibilities of redesign for installations in subsequently built piles.

REFERENCES

1. C. D. Coryell and E. Shapiro, Report CC-1310, May 3, 1944.
2. Katherine Way, Report MUC-KW-19, July 1, 1944.

Paper 6.2

USE OF HIGH-DENSITY RADIATION-ABSORBING SOLUTIONS IN OPTICAL INSTRUMENTS*

By P. R. Girardot

1. INTRODUCTION AND EXPERIMENTAL PROCEDURE

In the construction of over-all viewers, the complete protection of personnel was mandatory. The use of a radiation-absorbing solution instead of plain water in the optical path was suggested. The solution would have the added advantage that it would increase[1] the field of view of the instrument of whose optical path it was an element. Calculations[2] showed that a solution of $Pb(NO_3)_2$ of density about 1.3 increased the safety factor to between 10 and 20 times that of plain water, depending on the type of dangerous conditions which prevailed.

The question was next raised as to whether such a solution would become turbid as a result of interaction with the materials of which a viewer might be constructed. A number of solutions were suggested, and tests were conducted by D. D. Friel and the writer. The results of these tests are presented in Table 1.

The six pieces of materials placed in contact with the solutions are those most commonly used in building optical viewers and periscopes, in which the two plastics appear in the form of lenses. The containers for the tests were Lucite tubes with polystyrene plugs; the remaining four materials, as small samples, were inserted into the solutions contained within these tubes.

2. RESULTS

From Table 1 and from the actual appearance of the samples, it may be concluded that the solution of $ZnCl_2$ is the best of the four,

*The work described was done by P. R. Girardot and D. D. Friel.

Table 1—Reactions Between High-density Radiation-absorbing Solutions and Instrument Materials

			Effect on						
Solution	Conc., %	Density	Stainless steel	Brass	Plicene	Iron	Lucite	Polystyrene	Remarks
$Pb(NO_3)_2$	30	1.33	Slightly attacked	Very slight local action	None	Completely dissolved; red ppt.	Adherent white deposit on surface	Adherent white deposit on surface	Free Cl_2 present in quantity in container on opening
$NaNO_3$	43	1.35	Severely attacked; white ppt.	None	None	None (sample was galvanized)	Adherent heavy white film on surface	Adherent heavy white film on surface	
$CaCl_2$	35	1.34	Slightly attacked; reddish ppt.	None	None	Very slight	Very light white film on surface	Very light white film on surface	Solution remains quite cloudy
$ZnCl_2$	34	1.34	Very slightly attacked; white ppt.	Very slight local action	None	Very slight local action	None	None	Solution very clear

where the presence of all six materials is indicated. The utility of the other solutions in the absence of one or more tested materials may be readily determined from the table.

REFERENCES

1. C. D. Coryell and E. Shapiro, Report CC-1310, May 3, 1944.
2. Katherine Way, Report MUC-KW-19, July 1, 1944.
3. George S. Monk, Report MUC-GSM-126, July 6, 1944.

Paper 7.1

EXPERIMENTS ON THE EVAPORATION OF BORON IN VACUO*

By D. D. Friel

ABSTRACT

A method was needed to evaporate boron to form a rather pure uniform tenacious coat of specified thickness. These coats are needed as monitoring films for neutron intensities, particularly in steel ionization cylinders.

The most satisfactory method of evaporating boron employed a graphite filament. A mixture of amorphous boron and carbonoid A was painted onto the filament, which was then heated by electrical resistance to 2300°C, at which temperature the boron evaporated. Opaque films with purities up to 95 per cent boron or better could be deposited by this method. Much heat was liberated by the filament, and it was found necessary to cool the steel cylinders during evaporation to prevent the alloying of boron with the steel.

Cathodic deposition also proved satisfactory for producing high-purity films. Little or no heat is produced during the process, but the method requires much time.

Other methods, by which lighter films of boron were deposited, were less efficacious.

1. INTRODUCTION

The investigation of a satisfactory method for the evaporation of boron was begun in anticipation of the need for a more uniform and tenacious coat of boron than could be obtained by the existing methods of painting boron carbide with a binder. It was desired particularly to

*This paper is based on Report CP-1738, Mar. 31, 1944. The work described was done by D. D. Friel and L. O. Gilpatrick.

find a satisfactory coating for steel ionization chambers. At the beginning of this study no chemical means of depositing boron had been developed to such a point that it could be used.

2. GENERAL DISCUSSION

The evaporation of boron proved very difficult because of its high boiling point (2300°C), its high electrical resistance, and its tendency

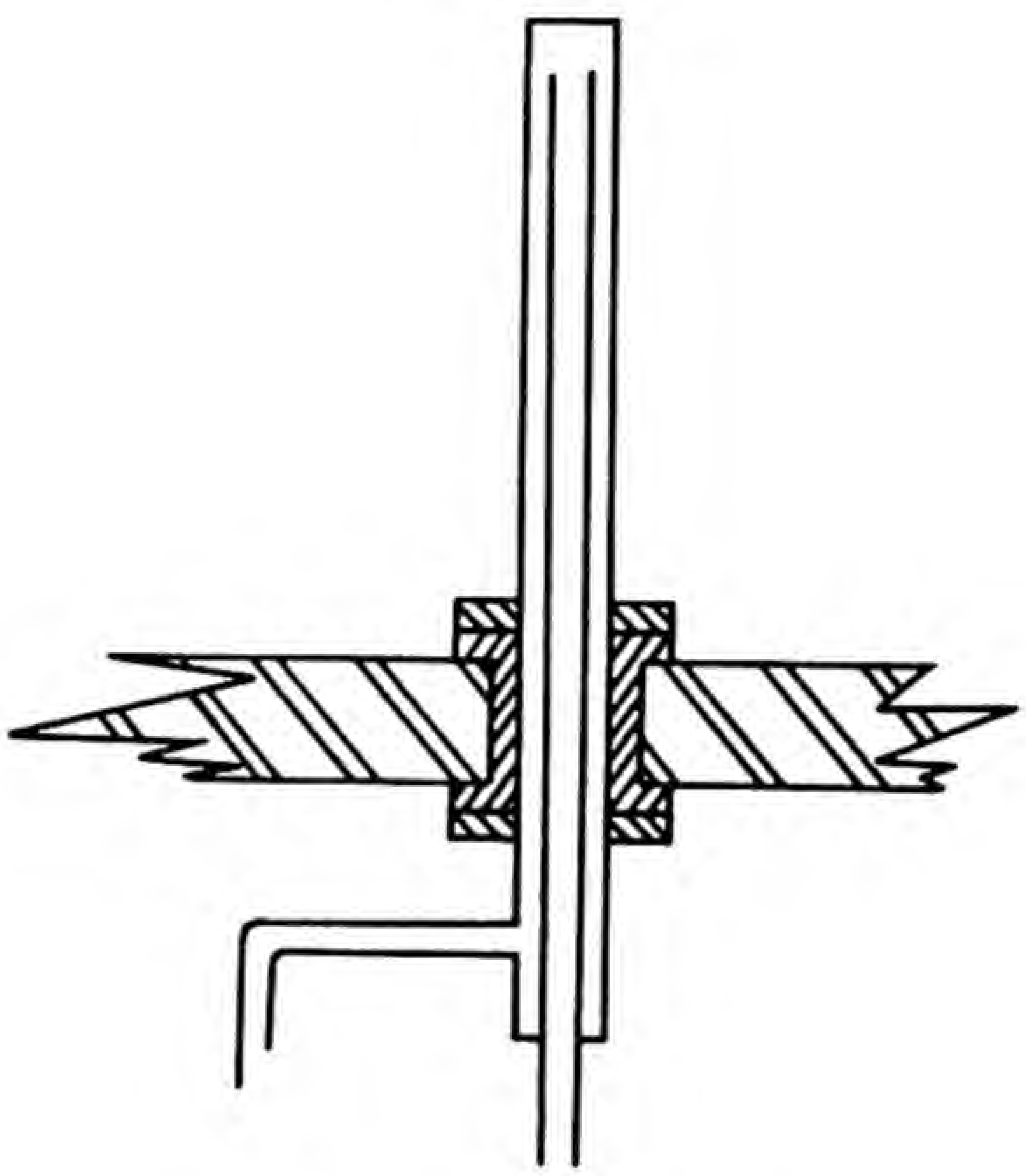

Fig. 1—Evaporation unit.

to react and alloy with most known substances. Another difficulty arose from the fact that pure boron is not obtainable and that impure material, which is obtainable, is in the amorphous form.

The evaporation systems used were designed to be quite versatile. Steel plates of various sizes, from 14 to 24 in. square, were used as the base plates for the systems. Through these plates were placed water-cooled electrodes insulated from the steel plates by various insulators (see Fig. 1). Holes about 2 in. in diameter were placed in the plates. Below the hole in the base plate was placed a diffusion pump of one type or another to evacuate the system. Mechanical pumps, such as the Hyvac, Megavac, and Hypervac, were attached to the diffusion pumps.

Bell jars of various sizes can be employed in such systems, their size being limited only by the position of the electrodes and the size of the steel plate.

3. EXPERIMENTAL WORK

The most common physical methods of depositing a metallic film coming under the heading of "evaporation" include: (1) direct electrical heating of the material to be vaporized, (2) indirect heating on a hot filament, (3) indirect heating in a refractory crucible, (4) cathodic deposition (sputtering), (5) electron bombardment, and (6) inductive heating. To coat a metal cylinder, the first four methods appeared best from a geometric and mechanical standpoint. The last two methods could be used only if sufficient equipment were available.

3.1 Tungsten Filaments. The first attempts were to vaporize some rather impure amorphous boron (57.7 per cent) from a horizontal tungsten filament wound in the form of a coil spring. This proved unsuccessful because the powdered material popped off as the coil heated. An attempt was made to use binders such as water, boron oxide, ammonium chloride, and small amounts of metallic magnesium and aluminum sulfate; however, in each case the boron popped off the filament before any appreciable evaporation occurred. Tungsten wire about 30 mils in diameter was wound into a helix or cone shape, but again the boron bounced off the wire or alloyed before evaporating. Also, tungsten strips proved unsuccessful as filaments because of the alloying and nonadherence.

Certain other steps were then taken in an attempt to keep the boron in contact with the tungsten. A tungsten coil of 30-mil wire and about ⅛ in. in diameter was placed through the center of a graphite crucible of ¼ in. diameter. The crucible was filled with boron, and the temperature was slowly raised. There was little evaporation because the coil failed owing to alloying with the boron. This was repeated about four times with tungsten rods of various sizes up to 1½ mm in diameter, but in each case the tungsten failed before any appreciable evaporation occurred. A 2-mm rod of tungsten about 8 in. long was heated over a 6-in. portion and reduced in diameter to 40 mils by application of sodium nitrite to the wire. This reduced portion was wound into a coil. This was then placed through a graphite crucible, as described above, the crucible being filled with boron. The reduced-diameter portion broke before any evaporation was noted, but an arc was formed between the unreduced portion of the rod, and this then gave rise to a rather dark coat. This method, however, seemed unreliable for reproducible coats, and the vacuum was hard to control. Also, the coating occurred only on a limited area above the crucible.

In another attempt to keep the boron from popping off the filaments, three perforated strips of sheet tungsten 10 mils thick, ⅜ in. wide, and 4 in. long were arranged lengthwise so that they formed a long tent of

triangular cross section, the sheets being fastened together by fine 10-mil tungsten wire. This was filled with amorphous boron, fastened between electrodes, and heated electrically. Several times by this method a fairly heavy coat (up to 2 wavelengths) resulted; however, the coat could not be regulated because of the irregularities in heating and construction. Also, the alloying was sufficient in most cases to cause the tent to break at high temperature.

3.2 Tungsten Stockings. Through courtesy of the General Electric Company, a so-called "stocking" of tungsten was obtained. This was essentially like the metal shielding used in electric cables. It could be obtained in various diameters and weaves and of most metallic wires up to about 20 mils; these experiments were based mainly on stockings of 240 strands of 3-mil wire of about ⅛ in. diameter. A number of experiments using these tungsten stockings were performed. The stockings were filled with amorphous boron and heated slowly, allowing sufficient time to degas the powder. These stockings held the boron tightly. With very careful control a light coat of boron could be obtained before alloying caused the setup to fail. The composition of this tungsten-boron alloy was determined as 91.1 per cent tungsten and 8.9 per cent boron. For most even heating of the stocking, it was found advisable to insert 2- to 3-mm tungsten rods in the ends of the stocking before placing it between electrodes. Variations of the above experiment were tried. Double stockings, one inside the other, were used with little more success than before. Also, a tungsten coil of 40-mil wire was wound, placed inside the stocking, and heated electrically. This was of some advantage, but still the coats obtained were unreliable and not too heavy. Some analysis of the films showed the percentage of boron to be as low as 10 per cent; however, not too much reliance could be placed in these results. Also, stockings of molybdenum and tantalum were obtained from the General Electric Company. These were filled with amorphous boron, and tungsten rods were inserted in the ends before the stockings were placed between electrodes. Again, in most cases, sufficient alloying occurred to cause failure of the system. It was found essential to have considerable degassing before raising the temperature above 2000°C. During evaporation boron readily forms a hydride if the pressure is too high; a vacuum of at least 10^{-4} mm Hg is necessary to avoid the formation of this material which gives a whitish coat to everything in the system. Various modifications to the above single-braid or stocking experiments were tried with molybdenum and tantalum. Combinations of tantalum, molybdenum, and tungsten stockings were tried, one being placed within the other; however, the boron alloys of these three metals are so definitely formed that obtaining a heavy coat of boron is impossible by these methods. Several attempts

to protect these stockings from alloying by painting them with light refractory coats proved unsuccessful because of cracking and sealing of the refractory.

3.3 Sintered Boron. Some attempts were made to form and sinter the powdered boron (57.7 per cent) obtained from the MacKay Company. A ⅛-in.-diameter cylindrical mold was made using a heavy-walled brass tube. The powdered boron was mixed with 5 to 10 per cent boron carbide and a few drops of phosphoric acid. This was then pressed into slugs in the mold and heated in a muffle to 800°C for 4 hr. These slugs hardened slightly but did not sinter. At the same time a porcelain crucible was filled with the powdered boron and heated for 4 hr to 80°C. The upper half of the crucible of boron was sintered, whereas the lower half remained powdery; the whole mass turned darker to an almost absolute black. The percentage of boron in the sintered portion was 29.5, whereas the percentage of boron in the still-powdery portion was only lowered to 48.5. These must represent oxides of boron with their present impurities.

The slugs thus formed appeared usable, and therefore they were placed in spirals of 30-mil tungsten wire and heated in vacuo. The vacuum was maintained at about 10^{-4} mm Hg as the temperature was slowly increased. A rather good boron coat resulted in many cases with careful temperature control; however, after long heating at high temperatures the alloying occurred and caused failure of the helix. Starting with the 29.5 per cent boron slugs, coats of 35 and 36 per cent purity were obtained. This indicates a very good quantitative method for deposition, but for heavy coats it is much too impractical. At a later date boron slugs were obtained in 12-in. lengths in diameters of 1/16 and 3/16 in. These were extruded through the cooperation of Globe-Union, Inc., Milwaukee. A purer boron (92.5 per cent) obtained from the City Chemical Corp., New York, was used to prepare these rods. Short pieces of these rods were heated in a helix of 30-mil molybdenum and tantalum wire. In the case of the molybdenum, an alloy was formed at 1950°C; it was of bronze-gold color and seemed fairly brittle. With tantalum wire the alloy was formed at 2250°C; again no appreciable evaporation occurred. One other experiment of this type was performed. A ⅛-in. slug of boron about ½ in. long was wrapped in a piece of 3-mil tantalum sheet and placed in a vertical tungsten coil. Heat was applied slowly until finally the whole mass alloyed into one lump; while this took place, a heavy dark-brown coat was placed on a glass plate about 6 in. away. This might be a coat of sufficient thickness for coating ionization chambers, but the method is prohibitive because of its expense and nonreproducible character.

3.4 Graphite Tubes. The next experiments were conducted with graphite tubes. Attempts were first made to evaporate amorphous

boron through the walls of thin-walled tubes of graphite that were heated electrically. High currents are required to heat carbon tubes of this nature to 2300°C. The power supply was, in general, a 220-volt supply with a water rheostat as a control resistance; currents as high as 250 amp were used with certain designs. The first tubes were about ¼ in. O.D., ³⁄₁₆ in. I.D., and 2 in. in length. The coats obtained had a dark appearance and a quite hard surface that did not tend to oxidize or hydrate. The method of mounting these tubes was quite critical to prevent localized heating. The most successful method employed end plugs of graphite that were about ½ in. in diameter, 1 in. long, and reduced in diameter on the end for a length of about ½ in. to the I.D. of the graphite tube in order that the plug could be slipped into the ends of the tube. A hole 2 mm in diameter was placed in the unreduced portion of the plug along the axis of the plug for a length of ¼ in. Pieces of tungsten rod 2 mm in diameter and 4 cm in length were placed in these holes and then clamped under a washer on the electrodes.

The tubes that seemed to give the heaviest coats were 0.15-in.-O.D. 0.12-in.-I.D. tubes of various lengths. The current had to be carefully controlled in order to prevent burning the tube. Although the coats were heavy and adherent, the chemical analysis showed discouragingly poor content of boron. The best coats showed a boron content of only about 12 per cent. It is to be realized, however, that it is extremely difficult to analyze accurately for boron as the base metal or in the form of boron carbide. Attempts to coat a copper cylinder using a carbon tube down its axis failed because of melting of the cylinder by the excessive heat. Slots about ⅛ in. long and ¹⁄₁₆ in. wide were placed at 120-deg intervals around a carbon tube of 0.15 in. O.D. and 0.12 in. I.D. The tube was filled with boron and heated electrically. Some boron popped out of the tube, but sufficient boron evaporated to give a dark-brown coat of 10 per cent. It was evident in these experiments that some alloying of the boron and carbon must have occurred. Another tube prepared with slots as above was coated inside and outside with boron carbide. This was filled with MacKay boron (having a purity of 57.7 per cent) and was heated electrically, maintaining a vacuum of 10^{-4} mm Hg. A fairly heavy blackish coat resulted on nearby plates. The film on the plate was analyzed volumetrically to have 33.8 per cent boron. The residue in the tube was analyzed and shown to have about 85 per cent boron. This offered a method of purifying somewhat the impure boron; some of this purified material was used in several subsequent experiments.

3.5 Refractories. Various experiments were conducted using refractories. Some of the crucibles used were made by the members of Magel's group; however, the first ones were made in this group. For

the production of these crucibles, a cylindrical mold of brass was used (see Fig. 2).

(a) Beryllia Crucibles. Beryllia crucibles were first made by using acid-washed beryllia that was ground extremely fine. This was dried and then mixed with very little water until the mixture appeared

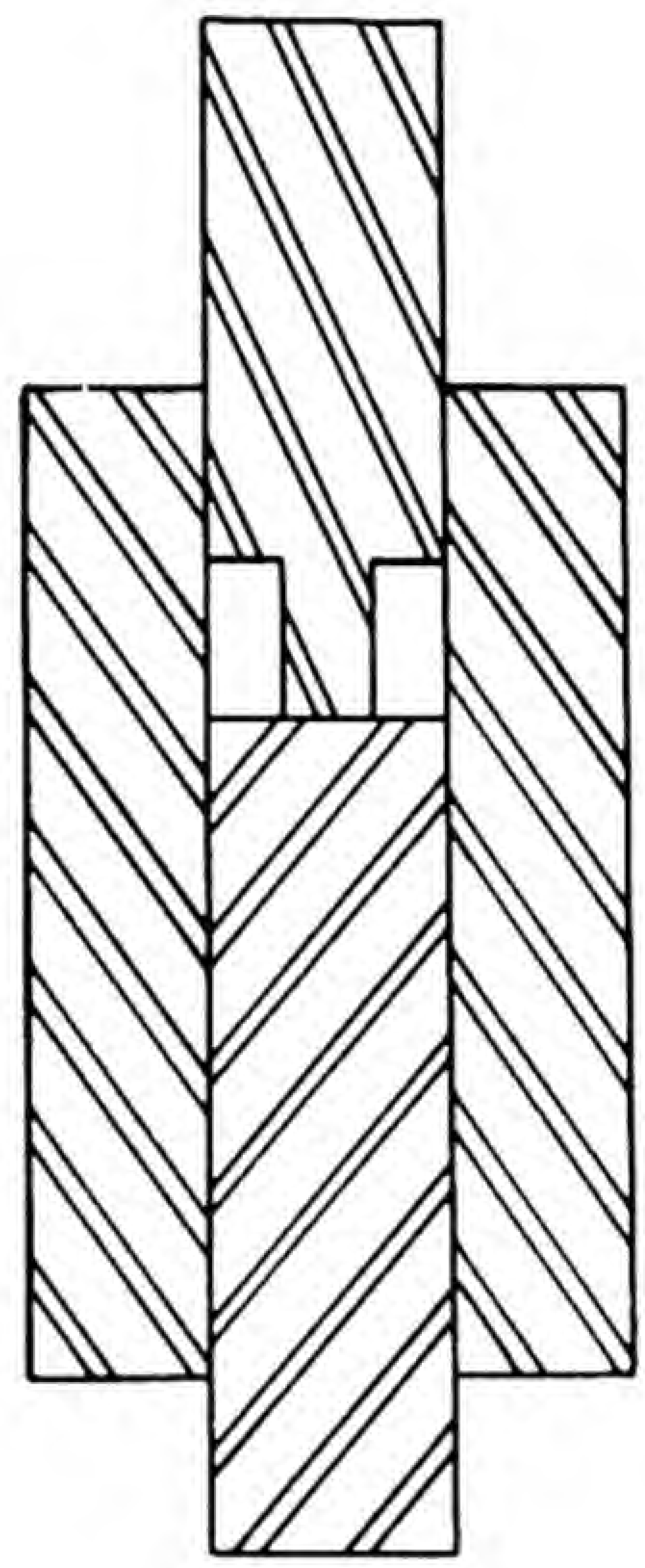

Fig. 2—Cylindrical brass mold used in production of crucibles.

slightly damp and crumbly. The mixture was packed in the mold and pressed with a hammer. The damp crucible was fired in a 1000°C oven for 4 hr and allowed to cool slowly. Several attempts were made to evaporate boron from these crucibles. The crucibles were placed in a coil of 30-mil tungsten wire and filled with amorphous boron. Slow heating was necessary to degas the crucible completely. The crucible softened where it was in good contact with the tungsten before a very heavy coat of boron was obtained. The coats produced were shiny black, adherent, and very light. This type of experiment was repeated using boron slugs in conical crucibles made by Magel's group, but again little of the boron evaporated before the crucible softened or before the tungsten coil failed.

(b) Thoria Crucibles. Thoria crucibles were prepared in the same mold as the beryllia crucibles and were pressed with a hammer. Thoria that was sintered and acid-bleached was reground finely and

wet slightly to a crumbly state. It was tamped in the mold and allowed to dry in air, forming a crucible 7/16 in. in diameter. The crucibles were heavy and a bit fragile. An improvement on this method was made by adding about 25 to 30 per cent thorium nitrate to finely ground thoria, not necessarily sintered and reground. This mix was wet slightly, pressed, and dried at room temperatures, thus forming stonelike crucibles. Also, ground cryolite and phosphoric acids mixed with thoria can be slip-cast successfully. In using these crucibles, it was found quite difficult to reach a sufficiently high temperature by using a tungsten coil alone. It was necessary to place a metal shield of tungsten or tantalum around the crucible and coil to obtain a coat. The coats obtained varied from a black to a shiny nature, and the percentage of boron in the films ranged from 16 to 38 using MacKay boron (57.7 per cent). This method gave sufficiently heavy coats, but only on intense and prolonged heating. Through the courtesy of Globe-Union, Inc., long tubes of thoria were obtained by an extrusion method. The tubes were 1/8 in. I.D., 1/4 in. O.D., and 13 in. long; some binder was used in the preparation of these tubes. One of these tubes was filled with some purer boron (92 to 95 per cent) obtained from the City Chemical Corp., and the tube was wrapped with a coil of tungsten wire. This was then arranged within a glass cylinder of 10 cm diameter and placed in the vacuum system. The coil was heated slowly with a pressure of about 10^{-3} mm Hg. Finally the coil sagged badly, and the thoria tube broke into short segments. The hard brown coat on the glass tube resembled the better boron coats and contained 25 per cent boron.

(c) Magnesia Crucibles. The greatest success with refractories was achieved using cylindrical magnesia crucibles that were prepared by Lawson at the University of Pennsylvania by a slip-cast method. In the first experiment, a crucible of this type was filled, placed in a tungsten coil, and supported by 1½-mm tungsten rods from below. The crucible was half filled with MacKay amorphous boron (57.7 per cent); it was then filled completely by the addition of beads of tungsten-boron alloy, made in previous experiments, to hold the boron in the crucible. After a long period of degassing, during which the temperature was raised slowly, a very thick, hard, tenacious coat was placed on the bell jar. The coat was opaque, brownish black, and of about 20 per cent reflecting power; it was analyzed to have 58.5 per cent boron, showing more than 100 per cent transfer to boron. An improvement in the ease of heating was made in some subsequent experiments by the use of a tantalum shield or larger refractory crucible around the crucible and coil, but the magnesia crucibles are easier to heat than beryllia or thoria crucibles. It was found that little evaporation occurred when several empty crucibles were heated

to about 2200°C; however, the crucibles' impurities deposited on the nearby plates as a milky-white film. With this concentrated heat the crucible became marblelike in appearance and quite hard, with some evidence of melting. Although the empty crucibles showed no evaporation, some of the coats produced must have been mainly magnesium.

The most successful evaporation from magnesia crucibles occurred using boron of 85 per cent purity (boron left as residue in a carbon-tube experiment). A small crucible of magnesia (7/16 in. in diameter) was placed in a tungsten coil. This was then surrounded with an alundum cylinder. Only a little boron of this purity was on hand; thus only a light coat was received. This film on glass plates contained 96.7 per cent boron. The test was repeated using boron of 92 to 95 per cent purity from City Chemical, and without the alundum shield. Two samples of this coat were separately analyzed; the percentages of boron were 16 and 59.1 in the samples, illustrating the unreliability of chemical methods of analysis of boron. Several times heavy coats with only 15 to 20 per cent boron were produced, indicating some evaporation of magnesium from the crucible. Although this method could be used to get boron coats, the temperature seems much too critical, and the impurity of magnesium would not be desirable in some cases.

(d) Boron Carbide Crucibles. Several boron carbide crucibles were made in the same mold used previously. The powdered carbide was mixed with phosphoric acid, pressed, and allowed to dry at room temperatures. These crucibles were quite hard and would withstand being dropped on the floor. A tungsten coil was wrapped around one of these crucibles, leaving a 1/32-in. gap around the crucible. An alundum shield was placed around this assembly. The crucible was filled with MacKay boron and heated for 3 hr at a pressure of 10^{-4} mm Hg. A rather unsatisfactory coat resulted (30 per cent boron); the carbide crucible disintegrated to a very porous state; and the alundum melted. This was not tried again because it was thought that insufficient heat could be applied by this method, and the crucibles did not hold up too well.

(e) Titanium Nitride Crucibles. Several titanium nitride crucibles, made using amyl alcohol as a binder and air dried, were quite satisfactory but a bit brittle. These were heated with a tungsten coil without much shorting out of the coil. Light coats were produced with 52 per cent boron. A harder crucible in cone shape was later furnished by Foster's group; this was a good conductor, causing the tungsten helix to short out and alloy with the crucible at a high temperature. This type of crucible could best be heated using induction currents; no generator of proper characteristics is available for this as yet.

(f) Thoria and Thorium Nitrate Coats. Attempts were made to protect filaments with refractories. A 1½-mm rod of tungsten was reduced in diameter at its center to about 30 mils. This was painted with a mixture of thoria and thorium nitrate and was placed in a boron-filled alundum boat. The coat protected the wire for a short time, but as the temperature rose the coat cracked, and the powdered boron sputtered out of the boat. A tungsten helix was coated with a mixture of titanium nitride and carbonoid A and was filled with boron slugs. This coat protected the wire for a considerable period; however, the wire finally broke after depositing a fairly heavy coat (47 per cent boron) on nearby plates. This also failed when magnesia was used in place of the titanium nitride. A tantalum-wire helix was coated with titanium carbide and heated with boron slugs. The wire broke at 2000°C before any evaporation occurred; another tantalum-wire helix was embedded in thoria, forming a solid crucible; this crucible withstood about 2250°C, but no heavy evaporation took place. The tantalum wire sagged badly with this construction and finally caused the system to fail; more experiments are planned with this type of crucible using a tungsten helix. Attempts to protect various metal stockings from alloying by using several refractories have thus far also been unsuccessful owing to cracking of the coats.

3.6 Carbon Filaments. The most successful method of depositing boron used carbon rods as filaments. For the first attempts carbon tubes were prepared by heating to a red heat and quenching in amorphous boron. When these tubes were heated by resistance heating, the coat peeled off the tube before much evaporation occurred. This was repeated with 2-mm-diameter rods of carbon, but again peeling occurred, and the rods broke and arced at high temperatures, giving rise to some carbon coat. The percentage of boron in the coat in one such experiment was 21 by analysis.

Later, ¼-in. tubes were painted with a mixture of carbonoid A (Zapon) and boron. When these were heated by passage of current, a blackish-brown coat resulted; the coat had a boron content of 95.6 per cent. This method was tried several times with smaller tubes (⅛ in. O.D.), but in each case these failed by breaking and arcing at a very high temperature. Eventually, tubes were abandoned in favor of carbon rods. First, a rod 4 mm in diameter and 5 cm long was turned down from a ½-in. rod of graphite. The ends of this rod were drilled, and 1½-mm rods of tungsten were inserted to act as supports for attaching to electrodes and to eliminate the heating of the brass washers used to clamp filaments to electrodes. The rod was painted with a thick mixture of carbonoid A and boron; after a degassing step, the rod was heated to 1950 to 2000°C, at which temperature the

rod broke. The coat produced was dark brown by transmission and exceedingly difficult to remove from glass. The film was estimated to contain 85 per cent boron; results of analyses were not dependable because of incomplete digestion of the samples. Rods of graphite (6 mm) held up very well with temperatures up to 2300°C. Very heavy tenacious coats of high purity were deposited on glass plates using these coated rods. Rods of 5½ mm diameter heated to 2400°C eventually broke and arced. After evaporation these carbon rods were covered with jet-black shiny fused areas which at times showed definite hexagonal-plate crystal patterns. In some experiments these crystals were found in large lumps; by microscopic inspection these plate crystals appeared much like those of pure boron observed by Laubengayer, Hurd, and others at Cornell.[1]

To test the efficiency of these boron coats as a neutron-monitoring agent, a steel cylinder about 4 in. in diameter and 11 in. long was coated. Carbon rods were prepared 5 mm in diameter and 12½ in. long with enlarged ends in which to insert tungsten leads. A rod was mounted vertically in a cylindrical metal bell jar and degassed to 2300°C. Then the test cylinder was placed around the carbon rod, and the system was resealed (see Fig. 3). At a low vacuum (10^{-4}), the temperature of the cylinder became quite high, and the boron penetrated deeply into the steel. This cylinder was only 37 per cent as efficient as a hand-painted coat of boron carbide and carbonoid A. It seemed necessary to provide a method of cooling the cylinder while it was being coated to prevent alloying; however, there is a temperature (about 200°C) below which the film on steel flakes off. A new evaporation unit providing water inlets could be used to cool the cylinder during evaporation. Temperature is a very critical factor. Of the various methods of evaporating boron using filaments, this carbon-rod method appears best from the standpoint of obtaining heavy coats of satisfactory purity.

3.7 Chemical Deposition. Wires of about 5-mil tantalum and tungsten were coated with boron by chemical deposition using diborane. These were heated electrically in an attempt to evaporate the boron; however, in all tests the wires failed at 1600 to 1700°C before any evaporation occurred. Larger wires may prove more satisfactory with less boron deposited on them.

3.8 Direct Resistance Heating. Rods of amorphous boron with a small amount of glycerine as a binder and lubricant were extruded from a small die. It was attempted to evaporate boron by direct resistance heating. Two coils of tungsten were used as end electrodes, and another coil was wrapped about the center of the rod. This arrangement was necessary because of the extremely high resistivity

(approximately 10^6 ohms) of boron at room temperature. At 1000°C the resistivity of boron becomes very low, and a high current can be passed through the material with a low voltage. The center coil was heated with 220 volts until the boron reached a red heat; then 220

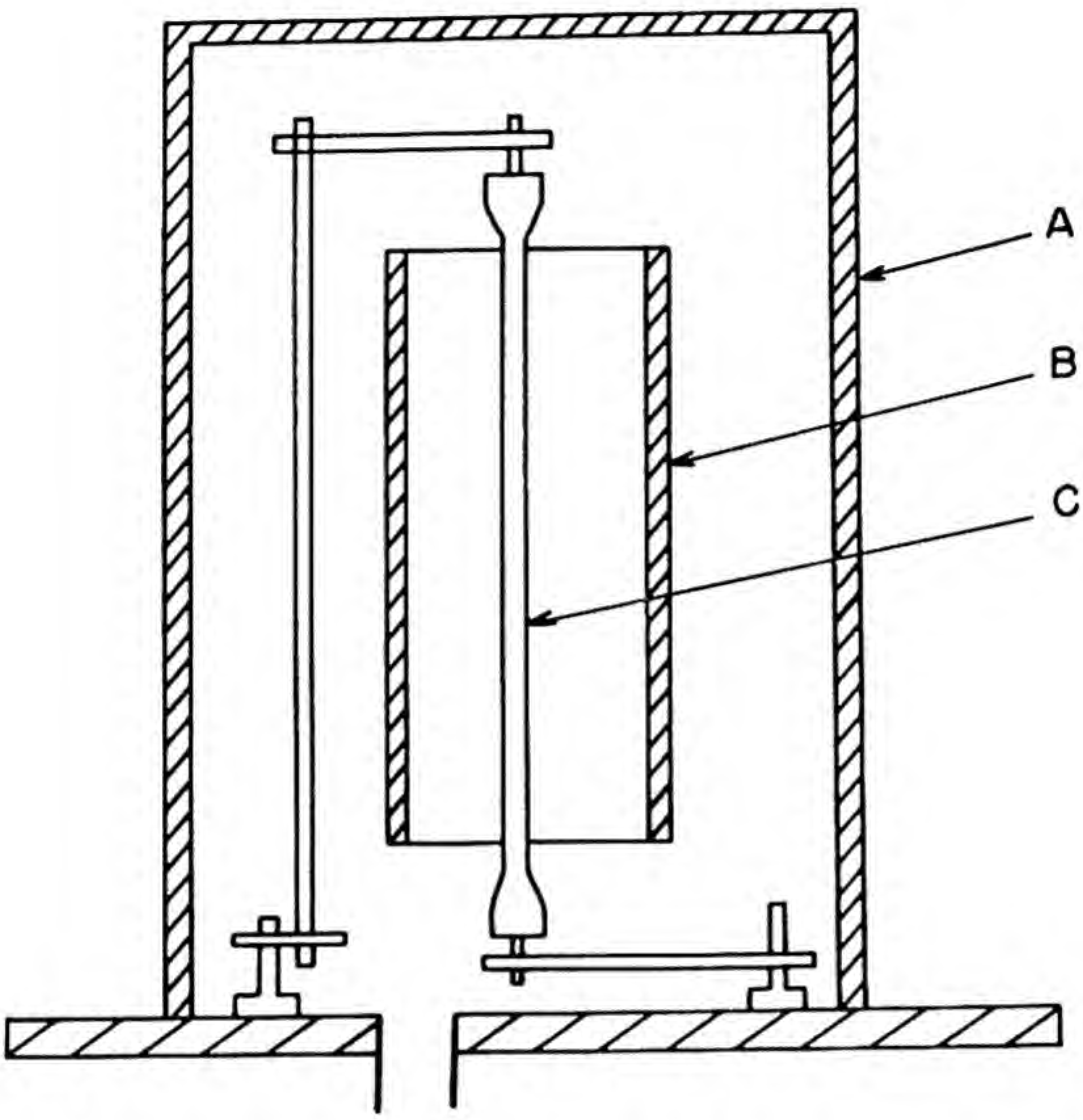

Fig. 3—Arrangement of carbon rod in test cylinder and bell jar. A, bell jar. B, test cylinder. C, carbon rod.

volts was placed across the rod. The rod heated rapidly because of its negative coefficient of resistance; it fused and produced a fairly heavy brown coat of 21 per cent boron by analysis. This method seemed promising, but the necessity for a variable voltage control was realized. Later, ⅛-in. rods extruded by Globe-Union, Inc., were used for this experiment. The rod was held by graphite blocks at each end. The tungsten coil was loosely wrapped around the rod to prevent alloying; this was an error because the rod could not be heated highly enough to get sufficient current through the boron rod with 220 volts. Similar experiments on direct heating of boron rods should be carried out when variable voltage supplies are available.

3.9 Evaporation of Boron by Use of an Arc. Several trials to evaporate boron by use of an arc were fairly successful. Great diffi-

culty was encountered in maintaining a high vacuum because of the rapid evolution of the gas arc. A 10,000-volt a-c transformer was used as the voltage supply. The arc was formed between two pieces of sintered boron (29.5 per cent boron), one held to an electrode in the plate and the other held to a flexible tungsten lead (1½ mm in diameter) from the top of the bell jar by light wire. The lead through the top of the bell jar was inserted through a rubber stopper; on the end of this, outside the jar, was a glass rod by which the tungsten lead could be controlled by hand and moved back and forth. A blue-green arc could be created between the pieces of sintered boron, but control of it was difficult. Owing to the high pressure during the arcing period, the coat went down on sample glass plates as a brownish-white coat, indicating the formation of oxides or hydrides; however, the coats were very tenacious. By analysis, the coats on the plates were 26 per cent boron, and the residue had risen in content to 33 per cent boron from its original content of 29.5 per cent. More experiments with completely degassed boron are planned.

3.10 Cathodic Deposition. Two tests were made on the feasibility of depositing boron by cathodic deposition. In the first trial, a rod of aluminum ⅛ in. in diameter and 8¾ in. long was coated with Zapon's carbonoid A, rolled in MacKay boron (57 per cent purity), and suspended vertically from the top of a high bell jar on a metal electrode that went through the jar. Around this cathode was placed a glass cylinder of 9.5 cm I.D. and 18 cm high. An aluminum strip 1½ in. in width was wrapped around this cylinder and connected to an electrode to form the anode. The system was evacuated, and a 3000-volt d-c power supply was applied between the cathode and anode; an automatically regulated maximum current for the power supply was 250 ma, but this probably was not obtained very frequently because of a tendency for the system to surge. The average voltage for the total of 13¼ hr was about 2700 volts; the dark space was regulated at about ½ to ¼ in. from the wall of the cylinder. A dark-brown film was deposited on the glass cylinder. Part of this was removed, weighed, and sampled. The coat was found to be about 40 μg/sq cm and to contain 42 per cent boron. Argon was used during part of the run, and a definite increase in the sputtering rate appeared to occur. Owing to flaking of the coat from the aluminum cathode, the cathode was changed three times; baking helped prevent this condition.

Another test of sputtering was performed using a $^3/_{16}$-in.-diameter 8-in.-long solid rod of extruded boron prepared by Globe-Union, Inc. This rod was mounted in a graphite block and was fastened to the top electrode of the bell jar. Much trouble was encountered in getting the system to settle to a constant current. The average voltage for 2½ hr

was about 1000 volts; a very-light-brown coat was deposited on the glass cylinder. This method provides a means of obtaining rather pure films of any thickness. The main objections to this method are that much heavy equipment is needed and the time necessary to produce heavy films may be rather long. With more power the time of deposition could be greatly reduced.

3.11 Electron Bombardment. Several attempts to obtain boron coats by electron bombardment showed that this method has promising possibilities. A ⅛-in.-deep graphite crucible (⅛ in. I.D.) was placed on a strong copper-wire support. Boron was placed in this crucible, which was surrounded by a coil of 30-mil tungsten wire (½ in. in diameter) for degassing and additional heat. This coil was heated to about 2300°C for 1 hr at 10^{-5} mm Hg pressure; then 10,000 volts (alternating current) from a ¾-kva Thordarson transformer was applied between the coil and the crucible. The temperature of the crucible increased slowly, and a deposit took place on nearby glass plates. The high-voltage power supply seemed inadequate for this type of experiment. This would be particularly true if heavy coats are to be produced. A 3000-volt 3-amp generator has been obtained, and more attempts to heat by this method will be made. It is realized that this method will only be applicable for coating objects of certain sizes and shapes; for coating the inside of cylinders this method would be very impractical.

4. RESULTS AND CONCLUSIONS

Evaporation methods of depositing boron are now developed to meet most needs. For the production of rather pure films of boron of considerable thickness, the method employing a carbon filament painted with a mixture of carbonoid A and boron seems most promising. Consistent coats of purity as high as 95 per cent could be produced in thicknesses up to about ½ mm or more.

For efficient coating of steel cylinders, it was necessary to limit the penetration and alloying of the boron by cooling the cylinders. The efficiency of coats placed on steel by chemical deposition is also dependent on temperature. For the coating of low-melting substances, cooling is absolutely necessary to prevent melting of the material. To determine the efficiency of the carbon-rod method, as compared with chemical deposition and mechanical painting, a cylinder that is cooled during the evaporation is tested. Films deposited by this procedure even without cooling methods are applicable for ionization chambers; however, their monitoring efficiency may not be as great as that of films deposited by other methods.

The cathodic-deposition methods are also capable of producing pure coats of thicknesses up to perhaps ½ mm. Temperatures could be maintained as low as 50°C for continuous operation during sputtering. The only disadvantages with this method are the time required for deposition and the initial cost of equipment. These difficulties forbid its use unless films produced by ali other methods fail.

For the preparation of thin films of high purity, tungsten wires or tents could be employed. For films of more than 1 wavelength, the method would be too costly, exceedingly slow, and unreliable for producing uniform coats. To obtain heavy films of up to 50 per cent purity, magnesia crucibles heated in tungsten coils could be employed. This method is quite rapid and capable of producing uniform tenacious films.

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Paper 7.2

SOME OBSERVATIONS ON CONTROLLED DEPOSITION OF METALS BY CATHODE SPUTTERING*

By D. C. Livingston

ABSTRACT

During an attempt to produce a transmission step wedge by cathode sputtering of platinum onto quartz, it was found that the rate of deposition of the platinum fluctuated. This appeared to be caused by the use of a mixture of gases instead of a single gas for a sputtering atmosphere, by distortions of the electric field, and by minor contributing factors. To avoid these effects, it seems advisable to design the system in such a way that electrostatic charge cannot accumulate on dielectric surfaces and to regulate pressure by means of a fast pumping system and a closely controlled valve admitting a single pure gas such as argon.

1. DESIRED PHYSICAL CHARACTERISTICS OF THE STEP WEDGE

The step wedge, intended for use in ultraviolet spectrometry, should consist of a platinum film deposited on one face of a quartz disk; the platinum serves as a transmission reducer, and the quartz serves as a carrier for the platinum. The disk, 5.0 cm in diameter and 0.2 cm thick, should be divided into five zones of platinum transmissivities,† 100, 33, 10, 3, and 1 per cent as measured at 3500 A. The zones should be distributed over the face of the disk as indicated in Fig. 1. The 10 per cent zone should be centered over the center of the disk.

*This paper is based on Report CP-2920, Apr. 18, 1945.

†By "platinum transmissivity" is meant the transmissivity of the platinum film alone; this would be the true transmissivity of the step wedge if the quartz were 100 per cent transmitting.

The 33, 10, and 3 per cent zones should each be 0.3 cm wide; the 100 and 1 per cent zones occupy the remainder of the surface. A spectrometer slit 1.5 cm in length could thus cover all five zones when placed as indicated by the dashed line. The transmissivities of all zones should be fairly close to the values given above, and the transmissivity should be highly uniform within any given zone.

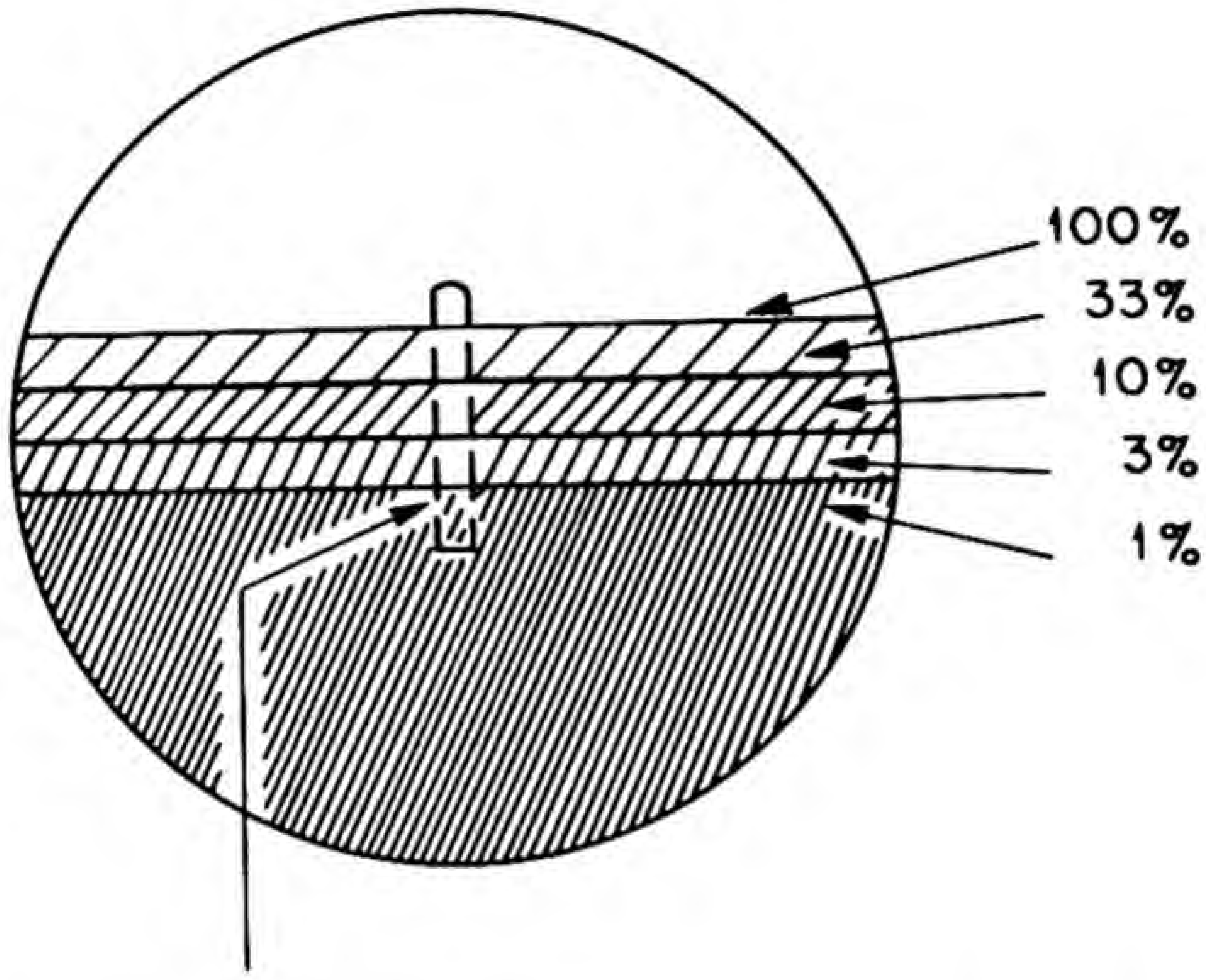

Fig. 1—Distribution of different transmission zones of the desired step wedge.

2. SPUTTERING APPARATUS

The apparatus shown in Fig. 2 was developed to produce this step wedge.

The pumping system consisted of a Cenco Hypervac mechanical pump and a mercury diffusion pump of glass construction. The latter was inoperative throughout the sputtering experiments since the mechanical pump alone was capable of attaining the desired degree of vacuum.

The high voltage required for the sputtering was obtained from a transformer-rectifier power supply capable of delivering any desired voltage up to 3000 volts as long as the current did not exceed 250 ma. Meters were provided for reading the voltage and current output.

The arrangement of parts within the bell jar was extraordinary in two respects. Because of the requirement that the quartz disk be coated in zones, it was necessary to provide a shield to define the edges of the zones. Further, it was considered desirable to cover all portions of the cathode plate and cathode support rod with glass for reasons which will be indicated later.

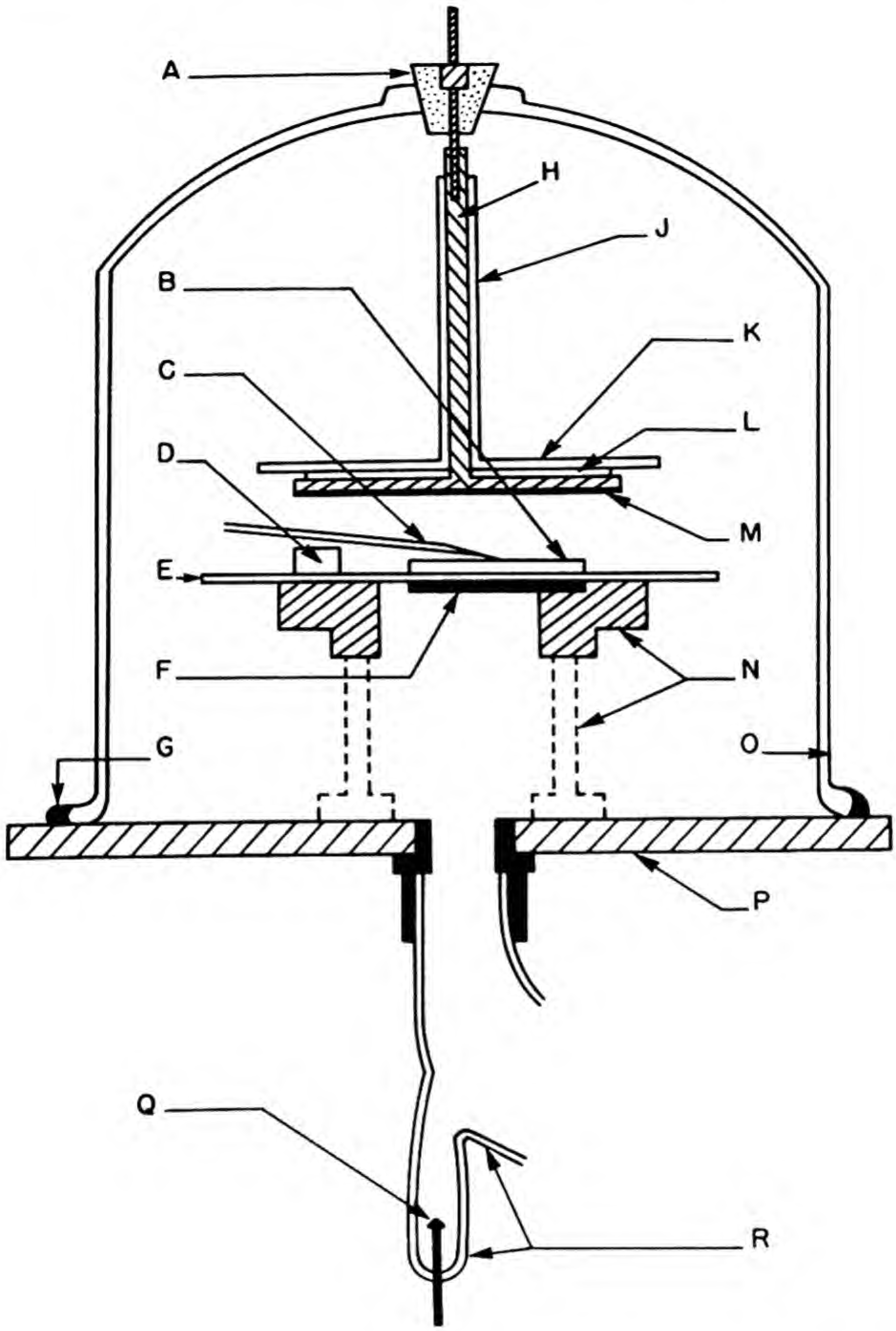

Fig. 2—Apparatus for producing the step wedge. The sizes of parts B, C, and D are exaggerated for clarity.

A, polystyrene insulator
B, quartz disk
C, glass shield
D, glass-shield raiser
E, glass support plate
F, paper zone guide
G, Apiezon Q vacuum seal
H, brass cathode support rod
J, glass current-limiting tube
K, glass current-limiting plate
L, aluminum cathode plate
M, platinum-foil cathode
N, metallic supports for support plate
O, glass bell jar
P, steel base plate
Q, anode
R, upper section of glass diffusion pump

3. PLAN FOR DEPOSITION OF STEPPED PLATINUM FILM

It was expected that a step wedge could be made through a series of sputtering exposures with the shield in a different position for each successive exposure. Thus, after each exposure, the shield could be moved to expose one more zone until only the 100 per cent zone remained under the shield. The duration of each exposure could be preassigned in accordance with what the results of previous experiments had indicated as optimum.

If sputtering current and pressure were kept constant so that, as a result, deposition rate, i.e., the mass of platinum deposited per unit area per unit time on the quartz disk, would be constant, it was expected that this method could be applied successfully. The thickness of a sputtered film, and therefore its transmissivity, would then be a function of sputtering time alone. The success of the method would be directly dependent on the efficiency of the regulatory system.

4. METHOD OF CURRENT AND PRESSURE STABILIZATION

The method of regulation used had been used very extensively and successfully in this laboratory for other sputtering operations.

The method consisted in applying a fixed voltage to the sputtering system and regulating the pressure in such a way that the current was kept constant. With the apparatus in the form shown in Fig. 2, the voltage and current standards were 800 volts and 25 ma, respectively. When the pump was running, the current gradually decreased; when the pump was shut off, the current increased. In either case, the current changed quite slowly, and regulation was an easy matter. Individual readings seldom deviated more than 1 ma from 25 ma, and the time average over even an interval of only 1 min was practically constant at 25 ma. This is considerably closer control than could be obtained by gauging pressure visually from the position of the Crookes dark space. The period of the pumping and resting cycle was usually about 5 min, during which time the pump was usually operated for between 2 and 5 sec.

Thus the voltage and current were held constant, and consequently the electrical conductivity of the sputtering system was constant. It is assumed that the pressure was also constant because the conductivity of a gaseous-discharge tube decreases with decreasing pressure at such pressures as were being used.

However, pressure is not the only factor which could influence the conductivity of a discharge tube. Changes can also be produced by such factors as fluctuation in composition of the gas and changes in

the form of the electrostatic field. The magnitudes of these effects are not known, but it is hoped that they were negligible.

5. EXPERIMENTAL RESULTS

Applications of this method were unsuccessful. The deposition rate fluctuated even though voltage and current did not vary. Different results were obtained from two runs performed with all controllable conditions the same for both. The results of these two runs are given in Table 1. The measurements were made in a Beckman spectrophotometer in an ultraviolet beam 10 A wide centered at 3500 A.

Table 1—Results of Attempts to Correlate Transmissivity and Sputtering Time

Desired transmissivity of zone, %	Measured transmissivity of zone	
	Step wedge A, %	Step wedge B, %
100	100	100
33	36.2	38.9
10	17.2	23.7
3	8.3	17.7
1	4.5	14.3

6. POSSIBLE CAUSES OF CORRELATION FAILURE

The cause of this failure to correlate transmissivity and sputtering time has not been established with certainty, but there are a number of factors which may have contributed. They are (1) occlusion of gas in the films, (2) partial sputtering of the films, (3) variation in composition of the gas, and (4) irregularities in the electric field. These will be discussed in order.

6.1 Occlusion of Gas in the Films. If more gas was absorbed in one film than in another while the films were being formed, these films might exhibit different transmissivities even though they contained equal amounts of deposited metal per unit area. If the amount of gas absorbed in a film is related to the length of time that elapsed between the first and the last step in its production, there is a good chance that different quantities of gas were absorbed on different films since the time interval was not necessarily the same for two otherwise similar films. The thicker parts of the films were deposited in separate layers as described in Sec. 1, and no check was maintained over the interval between deposition of successive layers. In the course of this work it has been assumed that the gas absorbed

or adsorbed during such an interval would be driven off quite thoroughly upon commencement of the next sputtering exposure.

6.2 Partial Sputtering of the Films. A secondary phenomenon occurring along with ordinary cathode sputtering is partial sputtering of the film on the receiving surface due to the impact of negative ions.[1] It is possible that this occurred to a greater extent on one film than on another, resulting in films of different thicknesses even though the exposure times were equal.

6.3 Variations in Composition of the Gas. Change in the composition of the sputtering atmosphere would change the electrical conductivity of the sputtering system and thereby upset the current- and pressure-stabilization system. The deposition rate would also be directly altered since two discharge tubes containing different gases but having all other factors alike exhibit different rates of sputtering.

The sputtering atmosphere consisted principally of nitrogen, oxygen, water vapor, and the oxides of carbon. A change in gas composition would be expected to occur, using the method of pressure regulation described in Sec. 4. Those constituents having the lowest diffusion rates would be pumped out less efficiently than those having higher diffusion rates. Thus the concentration of carbon dioxide should increase most rapidly, and that of nitrogen should decrease.

6.4 Irregularities in the Electric Field. The behavior of the electric field within the sputtering system probably contributed seriously to the correlation failure. Before describing this, it will be advisable first to define some terms as a precaution against ambiguity.

(a) Sputtering Current. Sputtering current is that current whose passage directly or indirectly causes deposition of sputtered material on the surface of the quartz disk.

(b) Nonsputtering Current. Nonsputtering current is that current whose passage causes no deposition of sputtered material on the surface of the quartz disk.

(c) Total Current. Total current is the sum of sputtering and nonsputtering currents; this is the current which is measured by the meter on the power supply.

(d) Sputtering Efficiency. Sputtering efficiency may be defined as the ratio of sputtering-current flux to total-current flux through a given area of the cathode.

(e) Deposition Rate. The deposition rate is the mass of sputtered material deposited per unit area per unit time on the surface of the quartz disk; it is proportional to the average sputtering efficiency for the entire cathode.

(f) Effective Sputtering Region. The effective sputtering region is that region on the cathode from which sputtered particles can readily reach the surface of the quartz disk by a short straight-line path.

With these definitions in mind, the influence of the electric field on deposition rate may be considered.

The various theories[2] on the mechanism of sputtering, although disagreeing on how the positive ions release metallic particles from the cathode, nevertheless agree almost without exception that the release of the sputtered particles is caused by the impact of positive ions upon the cathode. In the present application it is of great importance on what portion of the cathode the positive ions fall; where they fall is determined by the form of the electric field.

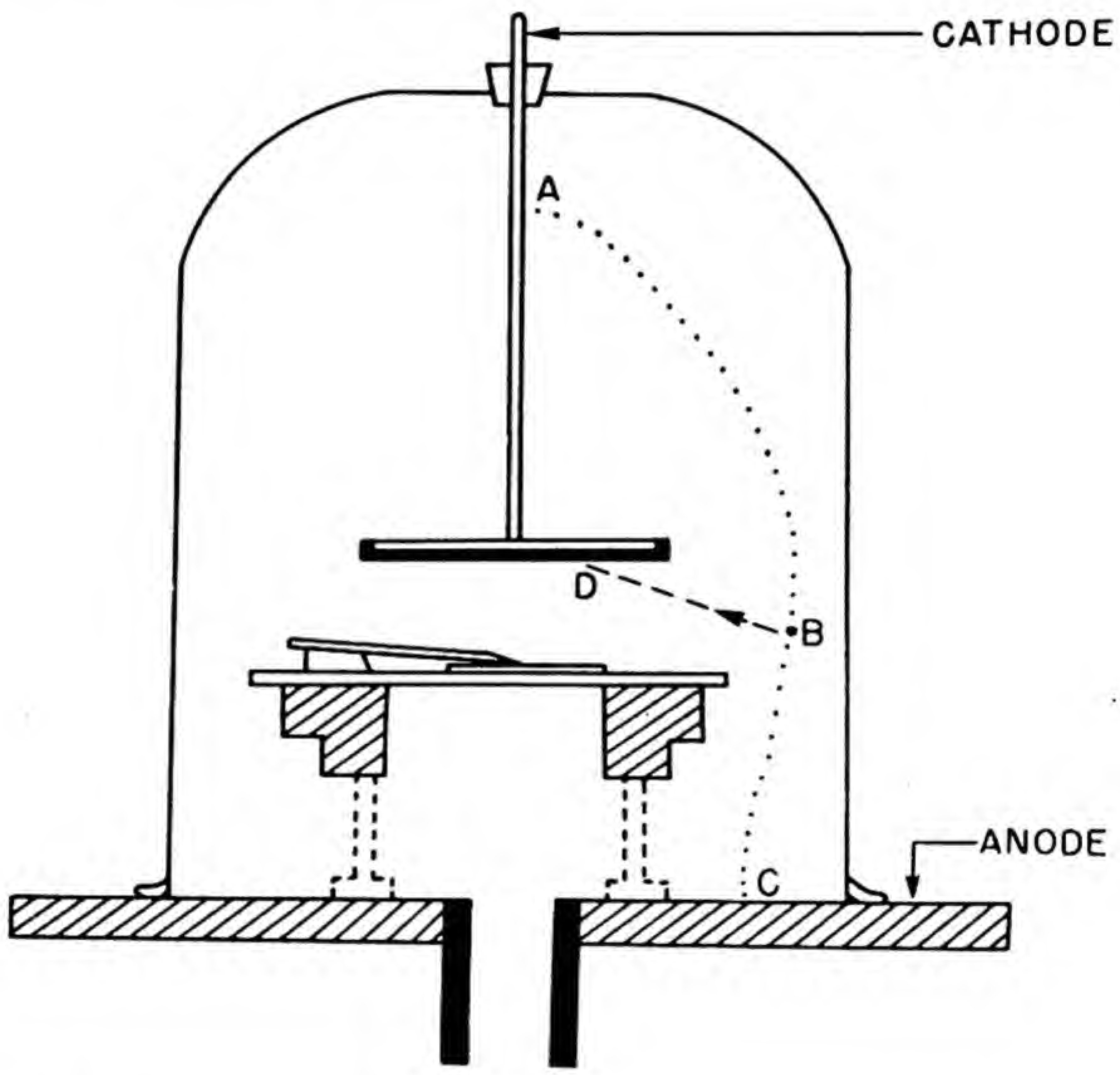

Fig. 3—Possible ion paths in sputtering systems.

The sputtering efficiency of a given area on the cathode surface depends upon geometrical factors in the manner shown in Fig. 3. This figure depicts the sputtering system used in the early experiments when the base plate served as anode and the upper cathode surfaces were not concealed under glass. The electric field may be supposed to be of such a form that an electron emitted at point A would traverse the path ABC to the anode. Along this path there would occur ionizing collisions of the electrons with residual gas molecules. A positive ion might be so formed at point B; it might then move along path BD and strike the platinum cathode surface at a

point D within the effective sputtering region. If this occurred, it might result in the ejection of a metallic particle which might fall upon the target. The sputtering efficiency at point A would have a value depending upon how many positive ions created by electrons from A can manage to fall into the cathode within the effective sputtering region.

The shape of the path ABC would depend upon the shape of the electric field. If the electric field changed in such a way as to cause a decrease in the distance BD, the probability that a positive ion might travel from B to D would increase. This would result in an increase in the value of the sputtering efficiency at point A. There have been strong indications that the form of the electric field has varied in such a way as to cause such fluctuations in sputtering efficiency over the entire cathode surface.

Visual examination of the sputtering system revealed that the glow discharge frequently changed in form. Dome-shaped regions of whitish luminosity occasionally appeared quite suddenly over a portion of the base plate which only a moment before had been covered by the normal pale-blue glow. The appearance of such a "dome" was always accompanied by more or less of a change in the distribution of light throughout the entire bell jar. It seems highly unlikely that this visual change was indicative of anything other than a change in the geometry of the electric field. It thus follows that the occurrence of the domes indicated that the form of the electric field changed and that, in turn, the distribution of values of sputtering efficiency over the cathode changed. When this happened, the average value of sputtering efficiency over the entire cathode also probably changed.

If the average sputtering efficiency changes, then, as can be seen from the definitions given at the beginning of this section, a change in the ratio of sputtering current to total current results. Such a change defeats the purpose of the current- and pressure-stabilization system since this system is based on the assumption that deposition rate will not vary if voltage, current, and pressures do not vary. However, deposition rate may vary even though these other quantities remain fixed because the current which was fixed was the total current rather than the sputtering current. In reality, it would be necessary to fix sputtering current in order to assure constant deposition rate. Only if the ratio of sputtering current to total current, or average sputtering efficiency, remained fixed, could constant total current indicate that sputtering current, and therefore deposition rate, was constant.

It becomes evident that the appearance of a luminous dome within the sputtering system was accompanied by a change in deposition rate.

7. REMEDIAL MEASURES

The first attempt at overcoming the effects of these electric-field irregularities involved installation of the current-limiting plate and tube shown in Fig. 2. This was done on the theory that it would decrease nonsputtering current far more than it would decrease sputtering current, with the result that the total current would more nearly equal the sputtering current and the average sputtering efficiency would thus increase. The effectiveness of this procedure depended upon the validity of the assumption that the surfaces covered were those of lowest sputtering efficiency. This assumption was based on the observation that positive ions and electrons are both motivated by the same electric field; thus positive ions should be most likely to strike the cathode surface near the point from which the electrons which created them were ejected. This would designate the effective sputtering region as the region of highest sputtering efficiency and the upper surface of the cathode plate and the surface of the cathode support rod as the regions of lowest sputtering efficiency.

When these current-limiting devices were installed and tested, it was found that they did limit the current as expected but that they produced no great improvement in the stabilization of deposition rate. There was great variation in sputtering efficiency even across the lower surface of the cathode, and consequently nonsputtering current could still comprise a significant fraction of the total current.

Second, the anode connection was transferred from the base plate to the electrode shown in the wall of the diffusion pump in Fig. 2. It was thought that this might stop the appearance of domes on the base plate and elsewhere. Actually, although it did stop their appearance over some parts of the base plate, domes appeared in some regions where they had not been observed previously. There was no net improvement.

These results indicated that the effects of electric-field distortions cannot be overcome except by a major redesign of the entire apparatus.

It is very likely that the cause of the distortion is the accumulation of electrostatic charge on the surfaces of insulators within the sputtering system. To prevent this, it would be necessary either to remove all such nonconductors from the system or to prevent them from collecting charge. The first step would be undesirable since the glass bell jar itself is undoubtedly the chief collector of charge, and there are practical reasons for not wishing to replace it with a metal one. The second step might be accomplished by utilizing the so-called "short-path idea" to keep the discharge away from the

walls of the bell jar. This principle has been used by Bush and Smith[3] to stabilize the discharge in glow tubes used in voltage-regulator service.

In view of the fact that this most serious difficulty was not readily overcome, no attempt was made to prevent effects due to changes in composition of the sputtering atmosphere, to occlusion of gas in the films, or to partial sputtering of the films. The only way to remedy the difficulties caused by fluctuations in the gas composition would have been to abandon the pressure-regulating system described in Sec. 4, and, instead, run both the mechanical pump and the diffusion pump continuously, admitting a single gas such as argon through a closely controlled needle valve.

Occlusion of gas in the films could not be prevented, but uniform occlusion might be sought by making the intervals between deposition of successive films equal for all films.

Partial sputtering of the films by negative-ion bombardment seems to be unavoidable except by such complicated arrangements as utilization of suitable deflecting fields. The effect probably is not serious enough to warrant such a measure.

8. TERMINATION STATUS

In view of the difficulties remaining to be overcome and practical considerations such as time involved and value of the step wedge once having been made, the work was discontinued. There seems little doubt, however, that the difficulties could be overcome satisfactorily if the value of the step wedge were great enough to warrant further investigation of the conditions within the sputtering system.

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Paper 7.3

PRODUCTION OF MIRRORS BY THE EVAPORATION PROCEDURE*

By Elaine Sammel Palevsky

ABSTRACT

Mirrors of high reflectivity and durability can be made by evaporating an alloy of 95 per cent aluminum and 5 per cent chromium. This composition was found to be more satisfactory than a 100 per cent aluminum mirror.

1. EVAPORATION PROCEDURE

Evaporation is carried out in a vacuum system using either a mercury diffusion pump with a liquid-air trap or a water-cooled oil diffusion pump. An initial vacuum of 10^{-4} mm Hg is reached before evaporation begins, and at no time during the process is the pressure allowed to exceed 10^{-3} mm Hg. The metal to be evaporated is heated by contact with a filament heated electrically in the vacuum. (For a general description of evaporation processes, see Monk[1] and Strong.[2])

Before a film is evaporated, the filament and metal are deoxidized. Two different procedures for deoxidation may be followed. Sometimes a shield operated by a magnet on the outside of the bell jar is inserted between the filament and the plate to be coated. After the prefiring, the shield is swung out of the way and the evaporation is performed. Sometimes, however, after the prefiring, the vacuum seal is broken in order that the plate can be inserted. After this, vacuum is obtained again and the evaporation is performed. For the purposes at hand the latter process was often just as efficient as the former.

*This paper is based on Report CP-3075, June 26, 1945. The work described was done by Elaine Sammel Palevsky and C. R. Botsford.

2. PRODUCTION OF GOOD MIRRORS

In the production of good mirrors by the evaporation method, the cleanliness of the plate and the composition of the reflecting film are of extreme importance.

2.1 Cleaning of Plates. For cleaning materials with a Mohs' hardness of 3 or more, such as plate glass, the mild abrasive action of a precipitated chalk slurry was very effective. All cleaning took place under running tap water, and the operator wore rubber gloves. The scratching effect of possible sediment in the tap water was found to be negligible. The plate to be cleaned was swabbed with absorbent cotton saturated with $CaCO_3$ suspension. This was rinsed in running water for 2 to 3 min. (The detail of sufficient rinsing is extremely important in the cleaning process.) The excess water was blown off the plate with compressed air. If any droplets ran across the dry portion of the plate in the blowing-off process, the plate was rinsed again. Finally, the plate was gently rubbed with clean absorbent cotton or lens tissue. The plate was tested by examining the breath figure caused by blowing gently on the plate. If breath upon the surface showed an even gray mist, the plate was considered to be clean; if there were imperfections in the breath pattern, cleaning of the surface was repeated.

2.2 Composition of Evaporated Coats. Pure aluminum mirrors were not considered satisfactory for Project purposes because, in spite of their high reflectivity, they are generally too soft and cannot withstand successive cleanings. When dust particles are removed with a soft cloth, pinholes are formed and the surface becomes scratched.

Evaporating first a thin coat of chromium or manganese and then a coat of aluminum did not produce a tough coat.

To produce a more durable coating, several aluminum alloys were tried. Table 1 shows the alloying elements, the amounts used, and some of their properties. A reflectometer should be used for comparing the reflectivity of different mirrors; however, since none was available, only visual comparison was made. Although the actual per cent of reflectivity could not be obtained, the better of two mirrors could be determined, and, to a certain extent, the reflection of different colors could be compared.

It was found that an alloy consisting of 95 per cent aluminum and 5 per cent chromium produced the toughest, hardest coat, with very high reflectivity. It cannot be positively ascertained, however, that the composition of the evaporated film is 95 per cent aluminum and 5 per cent chromium. It has been assumed that its composition is

the same as the original alloy. Because of the extremely small amount of metal deposited, quantitative tests as to the composition of the coating are very difficult to perform. However, a rough "spark" analysis showed the alloying element to be present in approximately the amounts expected.

Table 1—Summary of Tests on Different Mirrors

No.	Sample	Test performed: Scotch tape	Rubbing	Moisture	Scratching	Quality of reflecting coat
1	Al, 100%	Satisfactory	Rubs off to transparency immediately	Pinholes form	Scratches	Excellent
2	Mn, 5% 2S Al, 95%	Unsatisfactory	Rubs off	Not affected	Scratches	Dark
3	Mn, 5% Magnalium, 95%	Satisfactory	Rubs off	Not affected	Scratches	Dark
4	Co, 5% Al, 95%	Unsatisfactory	Rubs off	Not affected	Scratches	Dark
5	Cr, 1% Al, 99%	Satisfactory	Rubs off slightly	Not affected	Scratches	Excellent
6	Cr, 2% Al, 98%	Satisfactory	Rubs off slightly; better than 1%	Not affected	Scratches	Excellent
7	Co, 3% Al, 97%	Satisfactory	Rubs off slightly	Not affected	Hard to scratch	Excellent
8	Cr, 5% Al, 95%	Satisfactory	Little effect produced	Not affected	Hard to scratch	Excellent
9	Pt, 1% Al, 99%	Satisfactory	Rubs off only slightly	Not affected	Scratches	Excellent

3. TESTS AND RESULTS

The following tests were performed on the different plates shortly after they were removed from the bell jar:

1. Scotch-tape test. Scotch tape was applied to the surface and was then pulled off. If no change in the surface was visible, the coating was considered satisfactory.
2. Rubbing. The surface was rubbed with absorbent cotton.
3. Moisture. A thin film of moisture was formed on the surface by breathing upon it.
4. Scratching. The surface was scratched with a thumbnail.

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Paper 8.1

GRINDING AND POLISHING OF METALLIC MIRRORS*

By N. F. Beardsley

ABSTRACT

A discussion is given of numerous problems encountered in polishing metal mirrors of several different materials. The failures of certain methods are pointed out, and the most successful procedures are given in considerable detail.

1. INTRODUCTION

The Optical Shop undertook the task of developing methods for producing metallic mirrors more rugged and more corrosion resistant than those produced by evaporating silver or aluminum onto glass. This work falls into the following distinct sections:

1. The shape of the mirror and the thickness of the metal
2. The kind of metal to be used for the mirror
3. The mounting of the mirror for grinding, lapping, and polishing
4. The abrasives and polishing compounds to be used
5. The construction and material of the tools to be used for lapping and for polishing

2. THICKNESS OF THE METAL

Blanks of Stellite No. 6, ⅛ in. thick, were cemented by a soft wax (2 parts rosin to 1 part beeswax) to the surfaces of steel disks about ⅝ in. thick. It was exceedingly difficult to get these mirrors sufficiently flat. They changed shape while embedded in the wax; when they were removed from the wax, there was always a distinct warping of the surface. It was thought that this was due to aging of the metal

*This paper is based on Report CP-1684, May 10, 1944.

and that it could be stopped by accelerated aging. Therefore ⅛-in. mirrors, which had warped on being removed from the wax, were alternately frozen in dry ice for several hours, brought back to room temperature, heated to 140°C for several hours, and again brought to room temperature. After 5 cycles of heating and cooling, no appreciable change in the surface could be observed. The plates were then waxed to the steel plate and repolished flat. When they were removed from the wax, the warping reappeared immediately. In spite of the warping some of these mirrors rendered acceptable service at some locations.

Stainless steel type 440 was shaped for the mirrors, ground to about ⅛ in. thickness, heated to 1850°F, quenched in oil, reheated to 500°F for several hours, and cooled in the air. Such mirrors resembled Stellite in the difficulty encountered of flattening and warping after being removed from the wax; they contained intrusions of foreign material, probably carbides, which made them less acceptable than Stellite, and they showed no advantage over Stellite.

To prevent warping, mirrors ¼ in. thick were made of Stellite, type 440 stainless steel, type 18-8 stainless steel, hardened Stentor tool steel, and carburized cold-rolled steel. Stellite (⅛ in.) was soldered to a ½-in. brass plate and to a ⅛-in. brass plate, and No. 63 and No. 1 Stoodite were puddled on the surface of ½-in. steel. The ¼-in. Stellite and steels and the Stellite and Stoodite attached to the ½-in. base metal showed no signs of warping, but the ⅛-in. Stellite on ⅛-in. brass showed warpage. Thus warpage of ¼-in. straight metal or thinner metal cemented to a ½-in. back plate is not serious.

3. KIND OF METAL

Stentor tool steel, No. 1 and No. 63 Stoodite, carburized cold-rolled steel, No. 22 Stellite, Pyrasteel No. 2000, and small specimens of several other metals were also tried. Stoodite No. 63 was so difficult to work with that the welder could not puddle a homogeneous surface on the steel back; in fact, it was so hard that weeks of lapping and polishing did not produce a good surface. Stoodite No. 1 produced a satisfactory mirror. Aluminum could not be evaporated onto these steel mirrors in any way so as to cover up the pits. Therefore the use of hardened-steel mirrors coated with a more highly reflecting material is not advisable. Pyrasteel from a thin casting took a good polish but showed numerous pits caused by intrusions. If material were taken from the center of a larger casting, a very satisfactory mirror might be made from Pyrasteel. The best material to date has certainly been No. 22 optical Stellite.

4. MOUNTING OF THE MIRROR

The nonmagnetic Stellite mirrors were waxed to a steel plate to be held on the magnetic table of the hydraulic surface grinder. After removal from the grinder, the mirror, still attached to the steel plate, was put directly on the lapping and polishing machines. The mirrors were surrounded with blocks of the same material. This could be used only once since it had to be of the same thickness as the mirrors themselves.

To avoid using special blocks around each set of mirrors, they were mounted in plaster after being removed from the grinder. The mirror and the blocking material were coated with beeswax; the face of the mirror was firmly pressed against a lightly oiled optical surface; a ring was placed around the mirrors; about 1/16 in. of melted paraffin was flowed over the optical surface around the mirrors; and a mixture of 35 per cent Hydrocal A-11 with 65 per cent water was poured over the whole block. After setting, this block was slid off the optical surface, the metal ring was removed, and the surface of the plaster was waterproofed with a mixture of paraffin and beeswax. There was less warping with this method than with the method of waxing to a steel plate. Thus it is preferable to mount in plaster when the mirror is sufficiently thick that the plaster will hold it in place.

5. ABRASIVES AND POLISHING COMPOUNDS

Mirrors with the surface produced by the hydraulic surface grinder were first lapped with a moderately coarse abrasive. Here the word "lap" means the use of a hard tool, either steel, cast iron, or soft Arkansas stone with some abrasive, operated on a polishing machine. There seems to be little choice between the direct steel tools and the tools faced with soft Arkansas stone when lapping is started with either No. 400 or No. 800 boron carbide abrasive. On all these metals this abrasive produces a dull matte face which does not directly show fringes with a test plate but which can rather quickly be polished sufficiently to show fringes and hence to show the figure of the surface. Soft Arkansas stone and fine chromic oxide in water were tried for lapping. This was much slower than the coarser abrasive, but it produced a finish which showed fringes, and hence progress could be more directly observed. In spite of all efforts at cleanliness, an occasional bad scratch resulted; consequently it was quicker to lap the mirrors with boron carbide directly.

Lapping with No. 500 emery (crystallized alumina) and with Bausch & Lomb Optical Co. No. 2800 emery offered no advantage over going directly from the No. 800 boron carbide to the polishing process.

After the surface had been made reasonably fine and uniform and the tool marks of the hydraulic surface grinder had been removed, the surface was polished. Fisher's alumina (Fisher Scientific Co.) for hard metals produces a nice finish but may produce scratches and a bloom or grayish appearance over the surface. Cerium oxide showed no marked advantage. Most polishing has been done with very fine chromic oxide. The final finish was done with chromic oxide with individual particles no larger than 1 μ. Carefully washed tin oxide did not produce any better surface than chromic oxide and was more apt to cause scratches.

6. TOOLS FOR LAPPING AND POLISHING

Polishing tools which had long been successful in the polishing of glass were used first. These consisted of a pitch made by melting in an oven, at about 120°C, water-white rosin tempered with 7 to 9 per cent castor oil. The tools caused so many fine scratches, especially as the surface became rather perfectly polished, that other polishing materials were sought. Wax polishing tools of varying proportions, from 1 part beeswax per 4 parts rosin to 4 parts beeswax per 1 part rosin, were tried. They were relatively soft, did not flow evenly, and did not cause scratches so badly as pitch tools. They produced polished surfaces free from any serious scratches and almost free from fine scratches. They had to be abandoned because the lack of uniform flow made it difficult to get the mirror surface flat. By using castor oil–rosin tools and taking extraordinary precautions as to cleanliness, particularly by avoiding all hair edges on mirrors, by keeping the tools carefully trimmed, and by washing the mirror and the tools frequently with large quantities of distilled water, scratches can be kept to a reasonable minimum. Bitumen pitch, roofer's pitch which has been boiled down and hardened by the addition of rosin, is more satisfactory, however, than the rosin and castor oil pitch as a polishing agent.

The occasional appearance of bloom on the surface of the mirror has not been completely solved. Some modification of the polishing material or method is indicated. A cloth-faced tool might remove such bloom, but the use of a cloth always results in scratches. A cloth-faced tool might be useful in a completely dust-free air-conditioned room. Glass mirrors made with cloth-faced tools are never as good as glass mirrors made with pitch tools. It might be desirable to have a casting of Pyrasteel made, which would be particularly clean, if continued experimentation with metallic mirrors is desired.

Paper 8.2

WATERPROOF CEMENTS AND THEIR SUITABILITY IN OPTICAL CONSTRUCTION*

By K. F. Whitcomb

ABSTRACT

Tests were made on eight cements that were considered for use in cementing Lucite windows to brass parts of optical devices. Celluloid cement (cellulose nitrate or acetate dissolved in acetone) was found to meet the imposed requirements better than the other cements which were tested.

Cements of various kinds are widely used and offer a most important problem in the manufacture and construction of optical instruments to be used on this Project.

The particular problem that prompted the present investigation was the fastening of a Lucite window over the end of a brass tube, one end of which contained an 8-volt 1.15-amp electric bulb. The light in this case was used to illuminate the surface of a slug case. The requirements imposed on the cement for this job were as follows:

1. High strength in shear
2. Ability to wet both brass and Lucite surfaces
3. Ability to react with Lucite and brass or to be absorbed by their surfaces
4. Resistance to shock (not too brittle)
5. Waterproof
6. Melting point above 90°C

* This paper is based on Report CT-1392 (A-2033), Mar. 4, 1944.

Information is given in Table 1 on the various types of cements that were actually tried and the strengths of the joints obtained with the cements when fastening brass to Lucite.

Some of the cements, such as celluloid, methacrylate, and Belmont liquid solder, wet and adhered very well to both brass and Lucite.

Other cements, such as Boyer soil-pipe cement, Eureka cement, and Insalute No. 11470 (or sodium silicate), wet and adhered very well to brass but would not wet or adhere to Lucite.

In Table 2 is given information obtained from heat tests on the liquid-solder and celluloid-cement joints between brass and Lucite. Each of the cements produced joints which were not affected by the heating test (55 and 82°C for over 1 hr).

Data obtained when conducting a waterproof test on the liquid-solder and the celluloid-cement joints are reported in Table 3. The celluloid-cement joint was waterproof, but the liquid-solder joint was not.

In Table 4 is given some general information on other cements, some of which might prove satisfactory in fastening Lucite to brass. These cements were not tried. Judging from the information at hand, it is believed that the Cardo cement might prove the most satisfactory of those listed.

Table 1 — Tests on Brass-Lucite Cemented Joints Using Various Types of Cements

Cement No.	Type of cement	Manufacturer of cement	Types of joints and uses recommended by manufacturer	Procedure in making joint	Remarks
1	Methacrylate HE-225	Eastman Kodak Hawk Eye Works, Rochester, N. Y.	For cementing lenses and glass	Brass piece, 1/8 in. thick; Lucite strip and cement heated to 130°C before applying cement to brass and Lucite	Adheres very well to both brass and Lucite; forms brittle joint; by applying shock to joint in shear, Lucite broke off brass rather readily
2	Economy Plumber pipe-joint cement	Economy Plumber Co., New York, N. Y.	Prepared for use on iron and brass; steam, water, and gas piping joints will remain plastic on cold or hot parts and will not crack	Cement applied cold to brass and Lucite	After 36-hr drying in air, joint very weak, not entirely dried out, and very plastic
3	Celluloid, cellulose nitrate, or acetate	E. I. du Pont de Nemours & Co., Inc., Arlington, N. J.; Monsanto Chemical Co., Springfield, Mass.		A gummy mixture of celluloid in acetone applied to surface of 1½-in. cylinder of brass with 1/8-in. wall and to Lucite plane surface; brass cylinder rested on Lucite surface and allowed to stand	After 18-hr drying, it required a heavy blow with a hammer to break Lucite off brass cylinder; Lucite fractured instead of celluloid cement
4	Boyer soil-pipe cement	Boyer Chemical Laboratory Co., Chicago, Ill.	Prepared to form watertight joint between soil drain and sewer pipe	Powder mixed with water to form a putty-like consistency; mixture applied to 1½- by 1/8-in. surface of brass cylinder and to plane surface of Lucite; brass cylinder rested on Lucite	After few hours drying, formed a weak joint between brass and Lucite; did not adhere to or wet Lucite, but formed strong joint with brass

5	Belmont liquid solder	Butler Bros., Chicago, Ill., distributors	For wood, metal, glass, china, tanks, radiators, and pipes	Surfaces of Lucite and brass cleaned; thin layers of cement added to both and allowed to harden; second coat applied to each surface and 1½-in. brass cylinder rested on Lucite sheet for 18 hr	Excellent joint between brass and Lucite; wets brass and Lucite readily; also absorbed by Lucite or reacts to form very strong joint
6	Eureka cement	Eureka Cement Co., Chicago, Ill.	Mends china, glass, wood, leather, and water bags; waterproof	Surface of Lucite and brass cleaned; thin layers of cement applied to both; brass cylinder rested on Lucite until dry and hard	Rather weak joint formed in spots, stuck or adhered quite well to brass
7	Insalute No. 11470 or sodium silicate	Sauereisen Cements Co., Pittsburgh, Pa.	Used for assembling electrical insulation, acidproof construction bolt sealing, and double sealing furnaces; to make watertight, wash cement with dilute acid after drying	Surface of 1½-in.-diameter brass cylinder with ⅛-in. wall and Lucite cleaned; cement thoroughly mixed and thin layers applied to Lucite and brass; brass cylinder rested on Lucite and cement allowed to set	Joint very poor; cement adhered well to brass but not to Lucite at all; brass broke off Lucite very readily
8	Liquid solder plus Eureka cement	Butler Bros. and Eureka Cement Co.	For wood, glass, and china	Two cements mixed together; surfaces of 1½-in.-diameter brass cylinder with ⅛-in. wall and Lucite cleaned; thin layers of cement applied to both; brass cylinder rested on Lucite surface with no pressure	After 18-hr drying, brass cylinder pried from Lucite surface with very little effort

Table 2 — Heat Test on Brass-Lucite Cemented Joints

Type of cement used to fasten brass cylinder to Lucite window	Description of light box under Lucite window, etc.	Voltage and current on testing electric bulb	Length of time of heating, hr	Maximum temperature of surface of Lucite window above bulb, °C	Results
Liquid solder	Brass cylindrical lamp housing; lamp base secured in one end of cylinder; other end closed by disk of Lucite cemented to brass with liquid solder	6 volts; 1.15 amp	1	55	By applying a very high pressure to Lucite window, it was separated from brass at joint after heating test
Celluloid cement (celluloid dissolved in acetone)	Brass cylindrical lamp housing as above, except disk of Lucite cemented to brass with celluloid cement	8 volts; 1.15 amp	1½	82	After this heat test and a water test, a heavy blow with handle of hammer was required to separate window of Lucite from brass cylinder; the Lucite fractured instead of joint

Table 3 — Waterproofing Test on Brass-Lucite Cemented Joints

Type of cement used to fasten brass cylinder to Lucite window	Description of water container above the joint	Length of time cemented joint subjected to water, hr	Results
Liquid solder	Cylindrical brass tank about ½ in. high and 1½ in. I.D. set on a Lucite bottom and cemented to Lucite with liquid solder	24	Cement not waterproof; all water leaked out of ring in 24 hr, between ring and Lucite
Celluloid cement (celluloid dissolved in acetone)	Cylindrical brass tank as above, except Lucite bottom cemented to brass with celluloid cement	72	No leakage of water through celluloid joint after 72-hr test; small loss due to evaporation; cement waterproof; for strength of cemented joint after heat test and waterproofing test, see Table 2

Table 4 — Other Types of Cements Which Were Not Tried but Were Considered

Cement No.	Type of cement	Manufacturer of cement	Types of joints and uses recommended by manufacturer	Waterproof cement	Bond shear strength	Remarks
9	Rosin and castor oil			Yes	Low	Softens at room temperature; not rigid enough for holding Lucite window to brass shell above light of 8 volts 1.15 amp
10	⅓ beeswax and ⅔ rosin			Yes	Low	Softens in hot water; no good for window over 8-volt 1.15-amp bulb
11	Plicene cement	Central Scientific Co., Chicago, Ill.	For wood, glass, porcelain, metals, leather, etc.	Yes	Low	Melts at 80°C; thus, not satisfactory for window over 8-volt 1.15-amp bulb since it may reach 82°C
12	Cenco Sealstix, De Khotinsky cement, and shellac plus pine tar	Central Scientific Co.	Adheres to almost any surface	Yes	High strength, rather brittle	Surfaces to be cemented must be heated to 140°C; too high for Lucite to withstand; unsatisfactory for window over 8-volt 1.15-amp bulb
13	Babbitt, sealant Nos. 1, 2, 6, 8, 66, 74, 79, and 92	Babbitt Chemical Specialties Co., Inc., New York, N. Y.	A workable pipe joint for steam, alcohol, gasoline, oil, acid, ammonia, and for high hydraulic pressures	Yes		Since sealant is workable, it might be too plastic to hold window onto brass lighting holder in slug box; slug might easily knock off Lucite window
14	Norco cement	Norton Company, Worcester, Mass.	For fastening glass or quartz to iron or steel	Yes; also oilproof		

15	Marine glue, No. 11395	Central Scientific Co.				
16	Canadian balsam	Distributor: Central Scientific Co.	For cementing glass			
17	Cementyte cement, grade "A," hard	Schaar & Co., Chicago, Ill.	For joining glass, metal, and porcelain	Yes; also acidproof somewhat		Must be heated to 130°C as well as parts to be cemented; thus, it would be unsatisfactory for Lucite
18	Cardo cement, 250 series; vinylite cement	Cardo Chemical Co., Norwalk, Conn.	For metals, bakelite, glass, ceramics, and thermoplastics; baking temperature, 200 to 300°F	Yes; also resistant to vibration	About 4000 lb/sq in.	Due to (1) high curing temperature, (2) high shear strength, and (3) its waterproofness, it would probably be more satisfactory for Lucite brass joint than celluloid
19	Lubriseal	Arthur H. Thomas Co., Philadelphia, Pa.	For sealing desiccators and metal	Yes		Melting point 40°C; therefore unsatisfactory since temperature in use might reach 85°C
20	Cenco Softseal Tackiwax	Central Scientific Co.	For almost any material			Plastic at room temperature and high melting point; may be unsatisfactory because it is plastic and wax
21	Bakelite cement, No. 11420-A	Distributed by Central Scientific Co.		Yes, but not 100%	High strength but brittle	120°C curing temperature unsatisfactory for use on Lucite
22	Jewel cement	Hans Jensen Mfg., Chicago, Ill.	For many uses	Yes		Necessary to warm cement and objects before cementing to joints

INDEX

M

O

P